STATE OF CALIFORNIA
DEPARTMENT OF PUBLIC WORKS
DIVISION OF HIGHWAYS

CO-OPERATIVE TESTS OF PORTLAND CEMENT

SERIES OF 1956

FINAL REPORT

January, 1957

57-01

State of California
Department of Public Works
Division of Highways
MATERIALS AND RESEARCH DEPARTMENT
Sacramento, California

January, 1957

Mr. G. T. McCoy
State Highway Engineer
California Division of Highways
Sacramento, California

Dear Sir:

Submitted for your consideration is:

A report on

CO-OPERATIVE TESTS OF PORTLAND CEMENT

SERIES OF 1956

FINAL REPORT

Study made by . . . . Technical Section
Under general direction of. . . . . . Bailey Tremper
Report written by . . . . W. E. Haskell

Yours very truly

F. N. Hveem
Materials & Research Engineer

Dr. Botts:

This is your copy of our report on the co-op.

Our lab is "C" code letter

CO-OPERATIVE TESTS OF PORTLAND CEMENT

SERIES OF 1956

FOREWORD

A decision to initiate a co-operative series of tests of portland cement with the producers in California resulted from past experience which demonstrated that agreement was not always attained between our laboratory and the producer's laboratory as to the acceptability under the specifications of occasional shipments of cement. While such occasions have been relatively infrequent, they have served to raise questions as to reasons for such discrepancies and the allowance that should be made for the experimental errors that are inherent in any method of test.

ASTM Methods for Chemical Analysis of Portland Cement set forth the "Maximum Permissible Variations in Results" between two results or three results. Presumably these criteria apply to repetitions of determinations in a single laboratory but not to reproducibility between laboratories. No similar statements of permissible variation are given in the various ASTM physical test methods. Thus the ASTM methods provide insufficient guidance as to the normal expectation of variability in test results.

These co-operative tests, then, were planned to develop information on the variability of results. Tests were performed on three cements by the laboratories of cement producing mills in California and the Division of Highways.

The test results were compiled and analyzed for precision by methods of statistical analysis.

It is significant that no single laboratory was able to complete its portion of the test program without obtaining a substantial number of results that were "out-of-control" and which required elimination in the computations of valid statistical measures or precision. After out-of-control results were eliminated it was possible to compute values of repeatability within a single laboratory and reproducibility between laboratories. Such computations were made for those tests, which in the light of past experience, appear to be the most critical with respect both to reproducibility and the ability of manufacturers to meet specification requirements. The tests that may be considered to be the most critical in these respects are:

Alkalies

Autoclave Expansion

Strength

The results of the program bring out certain deficiencies in its planning and thus point the way to methods of obtaining more significant data with less effort in any future program.

CONTENTS

Final Report
of
Co-operative Tests of Portland Cement
Series of 1956

Test for:

Test for: Page

State of California
Department of Public Works
Division of Highways

MATERIALS AND RESEARCH DEPARTMENT

January, 1957

The experimental data discussed in this report were obtained as a part of a co-operative test series initiated by the Materials and Research Department of the California Division of Highways, and participated in by the laboratory of the Division, the laboratories of the eleven manufacturers of portland cement in California, and an out-of-state research laboratory, a total of thirteen participants.

The following is an alphabetical list of the laboratories which are referred to in this study by the code letters "A" to "M".

Blue Diamond Corporation
Mill at Los Angeles, California
Stuart R. Garnett, Chief Chemist

Calaveras Cement Company
Mill at San Andreas, California
M. C. Sutton, Chief Chemist

California Division of Highways
Materials and Research Department
Laboratory at Sacramento, California
F. N. Hveem, Materials and Research Engineer

California Portland Cement Company
Mill at Colton, California
W. C. Hanna, Vice President in Charge of Technical Development

Ideal Cement Company
Mill at Redwood City, California
H. W. Andrews, Chief Chemist

Ideal Cement Company
Research Laboratory, at Fort Collins, Colorado
G. C. Wilsnack, Director of Research, and
K. E. Palmer, Assistant Director of Research

Ideal Cement Company
Mill at San Juan Bautista, California
L. Caetano, Chief Chemist

Monolith Portland Cement Company
Mill at Monolith, California
John Partlow, Chief Chemist

Permanente Cement Company
Mill at Permanente, California
O. E. Jack, Chief Chemist

Riverside Cement Company
Mill at Crestmore, California
L. L. Cook, Chief Chemist

Riverside Cement Company
Mill at Oro Grande, California
E. A. Curley, Chief Chemist

Santa Cruz Portland Cement Company
Mill at Davenport, California
Norman Jones, Chief Chemist

Southwestern Portland Cement Company
Mill at Victorville, California
L. R. Indermuehle, Chief Chemist

The above list of participants is not in the same order as the letter designation assigned to them in this report.

Preparation of the Cement Samples

This study was intended to include all of the standard cement tests, and also some other tests which have not yet attained that status; and each laboratory was requested to perform duplicate tests on three samples of cement.

The cements included in the study were selected by the California Division of Highways, who communicated privately with three of the eleven manufacturers listed above, and requested them to furnish the cement. The selected manufacturers, each took 4 sacks of cement in succession from a single packing machine, and shipped them in waterproof bags to the Materials and Research Department in Sacramento.

Upon arrival at the Sacramento laboratory, each lot of cement was given a code number (1 to 3) for future identification. Each lot of cement was then mixed and subdivided by the following procedure.

One sack was emptied in the Lancaster mixer and mixed for one minute. Equal weights of the cement were then placed in four galvanized cans. The remaining sacks were then similarly treated. The contents of each of the four galvanized cans was then mixed for two minutes and returned to its can. Samples weighing 20 pounds each were weighed out in succession from the galvanized cans and placed in 1-gallon cans. Each can was marked with the proper code number. None of the samples showed a residue on the No. 20 sieve. In addition to the 20-pound sample, each co-operating laboratory was furnished with a carefully prepared sample of 40 grams of each cement in a sealed glass vial. This sample was for use in the specific surface tests and for the chemical analysis.

Three other samples of cement were also especially prepared by one of the cement manufacturers and sent to each participant for the "false set" tests. The samples prepared by the Division of Highways laboratory were, as heretofore noted, designated by the numbers 1, 2 and 3. The samples for the false set test were designated 4, 5, and 6. The two sets of samples were not related to one another in any way. The California Division of Highways laboratory was the only participant knowing the identity of samples 1 to 3. All participants knew that samples 4, 5, and 6, were prepared by the one manufacturer. All samples were transported in strong wooden boxes to the participating laboratories.

Results of the Tests

The complete results of all determinations by all of the participating laboratories are given in Tables I to XXVII. All of the data used in the statistical analyses of the results were obtained from these tables. Several previous reports have been issued on the results of a number of the tests and a summary of these reports are a part of this paper.

A number of statistical techniques have been employed in analyzing the results of the tests. A description of these methods is given below.

Statistical Methods Used in the Analysis of the Experimental Data

Control Limits for Averages ($\bar{X}$) and Ranges (R)

The observed variations in sets of observations such as are reported in this paper, are due to a variety of causes. It is impossible to state all of the reasons why repeated determinations differ from one another, or to specify why successive batches or units of material are not identical. Some of the causes of variation can be identified, and perhaps eliminated, and these are termed assignable causes of variation. There are other causes inherent in the analytical or testing procedures which are impossible to locate, and hence they cannot be removed. We designate these causes as unassignable or chance causes of variation; or sometimes as experimental, or residual error.

It is possible by using certain statistical methods to establish limits within which repeated determinations of some given characteristic will nearly always fall, providing that no assignable causes of variation are present. These limits are called "control limits" and the methods for computing them are a part of a statistical discipline known as statistical quality control (1,2)*. Values which lie outside of these limits are said to be "out of control", and unless it can be shown that the results obtained by the use of a given test method are within control limits, the method is considered to be unreliable. In this report control limits for averages ($\bar{X}$) and ranges (R) have been computed. Control limits are frequently represented graphically on "control charts".

Statistical Measures of Precision

In this paper the precision of a test method is considered as a measure of the closeness of the agreement between the results of a series of independent tests made on identical samples of material, when the conditions under which the method is used are well controlled. The average deviation is often used as such a measure but it is now being superseded by the standard deviation. The standard deviation is the root-mean-square deviation of the

*Figures in parentheses refer to references at the end of the paper.

observed values from their average. When the number of items in a sample is small, the standard deviation is the square root of the variance, and in computing a variance, the denominator is the degrees of freedom or N-1 in this case. Dividing the sum of squares by degrees of freedom makes a sample variance an unbiased estimate of the universe variance. The expression used for computing the standard deviation in this study is:

$$\sigma = \sqrt{\frac{\Sigma X^2 - \frac{(\Sigma X)^2}{N}}{N-1}}$$

in which

σ = The standard deviation
X = An item of data
N = The number of items of data
Σ = The sign of summation

The standard deviation may also be expressed as a percent of the average value, in which case it is called the coefficient of variation (v). This coefficient is useful in comparing sets of values with different absolute average values.

The standard deviation is a suitable measure of the precision of a single measurement. It also leads to an estimate of the precision of an average. This value, which is also termed the standard error of the mean, is computed by using the expression:

$$\sigma_{\bar{X}} = \frac{\sigma}{\sqrt{N}}$$

Statistical Measures of Repeatability and Reproducibility

The definitions and methods for computing repeatability and reproducibility are found in "Proposed Recommended Practices for Applying Precision Data Given in ASTM Methods of Test for Petroleum Products and Lubricants." (3)

In this publication, repeatability is defined as a quantitative measure of the variability associated with a single operator in a given laboratory, generally with the same apparatus, and within a small interval of time. It is the greatest difference between two single and independent results that can be considered acceptable at the 95 percent probability level.* The steps in computing repeatability involve first, the calculation of a value known as "repeatability standard deviation." The value of repeatability is then obtained by multiplying repeatability standard deviation by an appropriate factor which depends on the degrees of freedom (number of test results minus one). Estimates of repeatability standard deviations may be obtained by combining (pooling) the differences between results from each of several operators in different laboratories (carrying out the same determinations on identical materials) from his mean.

When k operators, each from a different laboratory produce a pair of results with differences of d_1, d_2, ... d_k, the repeatability standard deviation is given by the expression

$$S_r = \sqrt{\frac{d_1^2 + d_2^2 + \ldots + d_k^2}{2k}}$$

Reproducibility is defined as a quantitative measure of the variability associated with operators working in two different laboratories. It is the greatest difference between a single test result obtained in one laboratory and a single test result obtained in another laboratory that need not be considered suspect (significantly different) at the 95 percent probability level. When k operators each in a different laboratory produce results, the average of which is $\bar{X}_k$ and the grand average is $\bar{X}$, then the reproducibility standard deviation is

$$S_r = \sqrt{\frac{(\bar{X}_1 - \bar{X})^2 + (\bar{X}_2 - \bar{\bar{X}})^2 + \ldots + (\bar{X}_k - \bar{\bar{X}})^2}{k - 1}}$$

The value for reproducibility is obtained by multiplying the calculated value for S_r by an appropriate factor for the number of tests involved.

*Other levels of probability can be used but 95 percent is recommended in the reference cited.

The above definitions assume that the method of test is under control by the user, that is, that variations arising from assignable causes have been eliminated.

The Statistical Analysis of Variance

An analysis of variance is a statistical technique used in the examination of experimental data. (4)

If any set of observations is the result of one or more factors, the total variation between the observations in the set can be separated into components which can or cannot be attributed to the several factors, or to interactions between them. Statistical tests in the form of critical values are available for deciding which of the factors are associated with a significant fraction of the total variation. The results are usually classified as "highly significant", "significant", or "not significant." An interaction means the tendency for the combination of factors, say A and B, or A,B, and C, to produce a result that is different from the mere sum of their two or three individual contributions. The analysis of variance is especially useful when the effect of the factors or their interactions are not immediately obvious on visual inspection of the data. Interactions are represented by the notation A x B, or A X B X C, where the letters represent the different factors.

Analysis of the Tensile Strength Tests

The first tests discussed in this report are the tensile strength tests performed in accordance with A.S.T.M. Designation C 190-49 at 3 days and 7 days, and also the tensile strength test results obtained on similar mortars machine mixed according to A.S.T.M. Designation C 305-53T. The amount of water to be used in the several mortars was designated by the California Division of Highways and each laboratory used the same amount with a given cement.

The purpose of making the tensile tests was twofold; (1) to determine the correlation in results between laboratories and (2) to obtain data of use to the Working Committee on Strength of A.S.T.M. Committee C-1 in its consideration of the mechanical mixing of mortars in this test.

The complete results of the tensile strength tests are shown in Tables VI and VII. All tables designated by Roman numerals are at the end of the report, and they contain a complete tabulation of all of the results. Tables designated by Arabic numerals are in the body of the report and they record the results of the statistical analyses of the data.

Tables 1 and 2 show the results of the tests before the elimination of the out-of-control observations. Each tabulated value in these tables is the average of the tensile strength test on three briquets.

Table 3 shows the computed control limits for averages ($\bar{X}$) and ranges (R). All experimental values within these limits are comparable. In order to make a precise division it was necessary to compute the control limits to one-tenth of a pound per square inch, and in a number of cases an experimental value is in or out of the limits by a rather small amount.

Tables 4 and 5 are similar to Tables 1 and 2 except that the out-of-control values have been omitted and that the standard deviation in pounds per square inch and the coefficient of variation (in percent) of these averages is shown in the last two rows of the tables.

Figure 1 is an example of a control chart.

In both series of tensile strength tests and in the compressive strength test series, the computations for control limits were made on subgroups with three individual tests in each subgroup. These three individual tests were each from the same batch of mortar. For the thirteen laboratories, there were therefore, twenty-six subgroups considered.

We have now arrived at the tentative conclusion that the computations for control limits could more properly have been made using the two averages of each group of three tests as a subgroup, rather than by using the procedure as described above.

Probably this would have not brought all of the results within control limits, but the procedure seems to be more logical.

Table 1

Tensile Strength Tests of Three Portland Cements Designated 1, 2 and 3, by Twelve Laboratories Designated A to M According to ASTM Method Designation C 190-49
Each Tabulated Value is the Average of Three Briquet Tests

Lab.	Test	3 Days			Avg.	7 Days			Avg.
		1	2	3		1	2	3	
A	1	268	240	307	273	350	307	387	348
	2	262	248	303	271	353	312	378	348
	Avg.	265	244	305	271	352	310	382	348
B	1	272	233	241	249	338	295	334	322
	2	270	236	238	248	345	305	339	330
	Avg.	271	234	240	248	342	300	336	326
C	1	298	248	335	294	395	331	403	365
	2	302	245	338	291	377	351	362	363
	Avg.	300	246	336	294	386	341	382	364
D	1	292	247	355	298	353	325	405	361
	2	298	260	327	295	345	320	390	352
	Avg.	295	254	341	296	349	322	398	356
E	1	300	255	333	296	407	390	422	406
	2	295	225	322	281	373	312	397	361
	Avg.	297	240	328	288	390	351	408	383
F	1	257	237	330	274	343	320	318	327
	2	282	242	405	309	347	315	415	359
	Avg.	270	240	368	292	345	318	366	343
G	1	262	248	283	264	387	312	401	366
	2	248	233	316	266	372	312	412	365
	Avg.	255	240	300	265	380	312	406	366
H	1	208	200	280	229	295	270	353	306
	2	265	233	315	271	345	298	383	342
	Avg.	236	216	298	250	320	284	368	324
I	1	228	195	285	236	363	298	328	330
	2	262	210	267	246	363	340	360	354
	Avg.	245	202	276	241	363	319	344	342
J	1	262	218	306	262	376	303	360	347
	2	322	242	304	289	342	321	408	357
	Avg.	292	230	305	276	359	312	384	352
L	1	295	235	315	282	340	325	390	352
	2	257	213	307	259	368	312	388	356
	Avg.	276	224	311	270	354	318	389	354
M	1	297	247	309	284	363	356	425	381
	2	334	246	325	302	444	350	430	408
	Avg.	316	246	317	293	404	353	428	395
Grand Avg.		276	235	311	274	362	320	381	354

Table 2

Tensile Strength Tests of Three Portland Cements Designated 1, 2 and 3, by Twelve Laboratories Designated A to M According to ASTM C190-49 and Mixed According to ASTM C305-53T
Each Tabulated Value is the Average of Three Briquet Tests

Lab.	Test	3 Days				7 Days			
		1	2	3	Avg.	1	2	3	Avg.
A	1	307	243	343	298	395	317	408	373
	2	292	250	347	296	373	308	411	364
	Avg.	300	246	345	297	384	312	410	368
B	1	303	198	292	264	404	324	431	386
	2	311	203	294	269	405	319	431	385
	Avg.	307	200	293	266	404	322	431	386
C	1	308	226	362	299	415	308	444	389
	2	312	229	348	296	413	329	451	398
	Avg.	310	228	355	298	414	318	448	394
D	1	288	237	325	283	368	333	370	357
	2	308	230	328	289	338	333	412	361
	Avg.	298	234	326	286	353	333	391	359
E	1	298	238	353	296	373	307	417	366
	2	265	262	367	298	358	287	418	354
	Avg.	282	250	360	297	366	297	418	360
F	1	276	235	303	271	373	320	407	367
	2	242	258	295	265	382	296	386	355
	Avg.	269	246	299	268	378	308	396	361
G	1	277	217	320	271	363	288	408	353
	2	280	227	308	272	367	327	420	371
	Avg.	278	222	314	272	365	308	414	362
H	1	273	213	302	263	326	345	388	353
	2	273	210	284	256	327	290	352	323
	Avg.	273	212	293	260	326	318	370	338
I	1	240	228	278	249	352	285	373	337
	2	238	193	280	237	353	323	367	348
	Avg.	239	210	279	243	352	304	370	342
J	1	297	238	326	287	369	319	372	353
	2	276	250	329	285	356	332	394	361
	Avg.	286	244	328	286	362	326	383	357
L	1	295	233	305	278	381	325	408	371
	2	255	212	308	258	361	298	408	356
	Avg.	275	222	306	268	371	312	408	364
M	1	285	269	329	278	391	317	412	373
	2	295	236	336	289	403	354	432	396
	Avg.	290	252	332	284	397	336	422	384
Grand Avg.		283	231	319	277	373	316	405	364

Table 3

Computed Control Limits for Averages ($\bar{X}$), and Ranges (R), for Tensile Strength Tests

Standard Hand Mixed Mortars

Cement Number	Age, Days	Grand Average $\bar{\bar{X}}$	Average Range $\bar{R}$	Computed Control Limits: Average $\bar{X}$ UCL*	Computed Control Limits: Average $\bar{X}$ LCL**	Computed Control Limits: Range R UCL	Computed Control Limits: Range R LCL
1	3	278.7	25.3	304.6	252.8	65.1	0
2	3	239.9	24.0	264.5	215.3	61.8	0
3	3	312.6	40.0	353.5	271.7	103.0	0
1	7	355.6	26.6	382.8	328.4	68.5	0
2	7	313.6	27.3	341.5	285.7	70.3	0
3	7	387.8	33.9	422.5	353.1	87.3	0
Machine Mixed Mortars							
1	3	288.4	27.6	316.6	260.2	71.3	0
2	3	232.2	27.2	260.0	204.4	70.0	0
3	3	315.3	28.4	344.1	286.5	72.6	0
1	7	373.4	36.6	410.8	336.0	94.2	0
2	7	312.0	29.4	342.1	281.9	75.7	0
3	7	405.5	35.4	441.7	369.3	91.2	0

*UCL = Upper Control Limits
**LCL = Lower Control Limits

Table 4

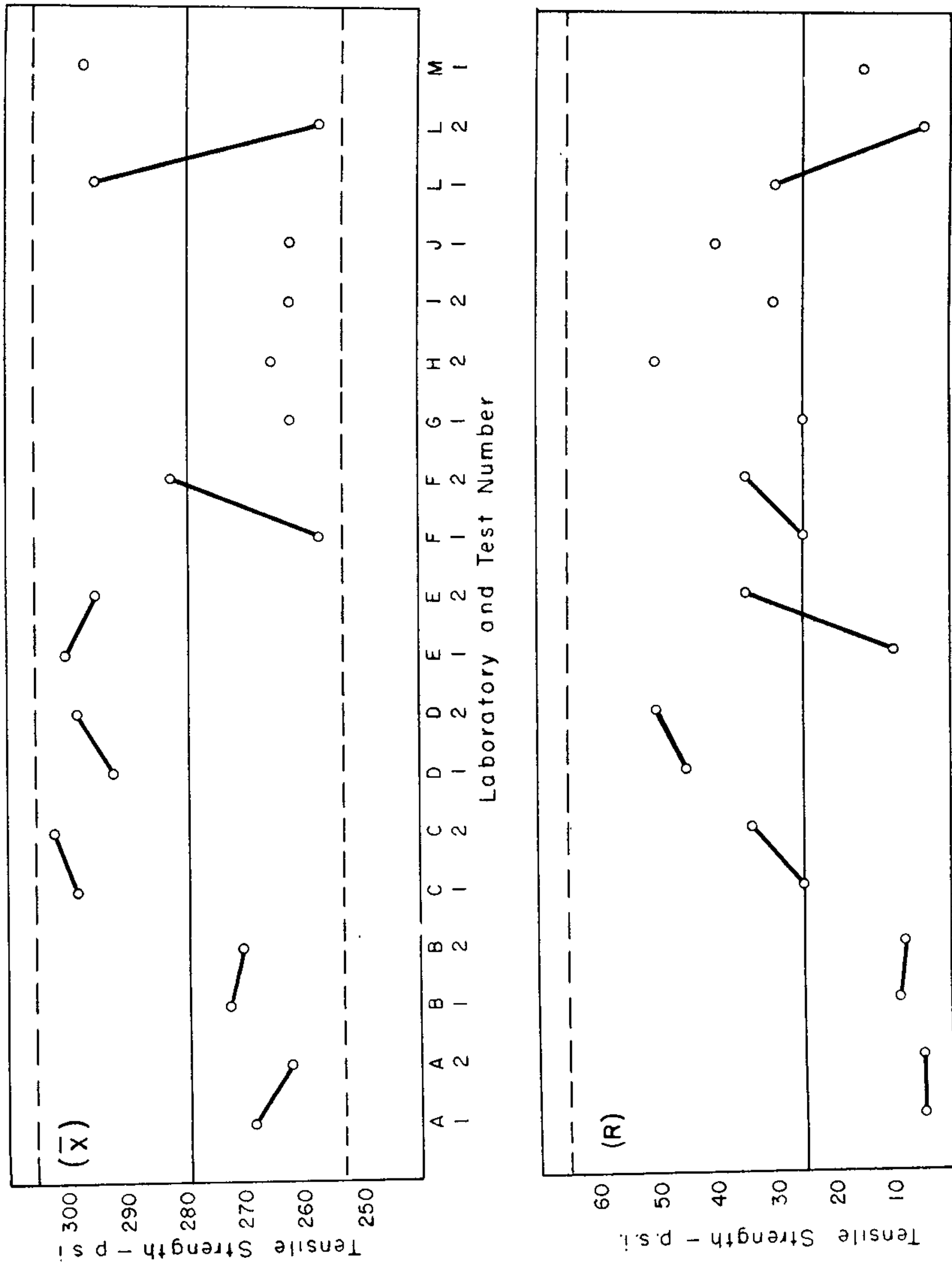
Tensile Strength Test Results in Statistical Control from Tables 1 and 3

Lab.	Test	3 Days 1	3 Days 2	3 Days 3	Grand Avg.	7 Days 1	7 Days 2	7 Days 3	Grand Avg.
A	1	268	240	307		350	307	387	
	2	262	248	303		353	312	378	
	Avg.	265	244	305		352	310	382	
B	1	272	233	X		338	295	X	
	2	270	236	X		345	305	X	
	Avg.	271	234	X		342	300	X	
C	1	298	248	335		X	331	403	
	2	302	245	338		377	X	362	
	Avg.	300	246	336				382	
D	1	292	247	X		353	325	405	
	2	298	X	327		345	320	390	
	Avg.	295				349	322	398	
E	1	300	255	333		X	X	X	
	2	295	225	322		373	312	397	
	Avg.	297	240	328					
F	1	257	237	330		343	320	X	
	2	282	242	X		347	315	415	
	Avg.	270	240			345	318		
G	1	262	248	283		X	312	401	
	2	X	233	316		372	312	412	
	Avg.		240	300			312	406	
H	1	X	X	280		X	X	353	
	2	265	233	315		345	298	383	
	Avg.			298				368	
I	1	X	X	285		363	298	X	
	2	262	X	X		363	340	360	
	Avg.					363	319		
J	1	262	218	306		376	303	360	
	2	X	242	304		342	321	408	
	Avg.		230	305		359	312	384	
L	1	295	235	315		340	325	390	
	2	257	X	307		368	312	388	
	Avg.	276		311		354	318	389	
M	1	297	247	309		363	X	X	
	2	X	246	325		X	X	X	
	Avg.		246	317					
Grand Avg. ($\bar{X}$)		279	240	313	277	356	314	388	353
St. Dev. (σ)		17	9	17	14	13	12	19	15
Coeff. of Var. (V)		6.2	3.8	5.5	5.2	3.7	3.8	4.9	4.1

Table 5

Tensile Strength Test Results in Statistical Control
From Tables 2 and 3

Lab.	Test	3 Days 1	3 Days 2	3 Days 3	Grand Avg.	7 Days 1	7 Days 2	7 Days 3	Grand Avg.
A	1	307	243	343		395	317	408	
	2	292	250	X		373	308	411	
	Avg.	300	246			384	312	410	
B	1	303	X	292		404	324	431	
	2	X	X	294		405	319	431	
	Avg.			293		404	322	431	
C	1	308	226	X		X	308	X	
	2	X	229	X		X	329	X	
	Avg.		228				318		
D	1	288	237	325		368	X	370	
	2	308	230	328		338	333	412	
	Avg.	298	234	326		353		391	
E	1	298	238	X		373	307	417	
	2	265	X	X		358	287	418	
	Avg.	282				366	297	418	
F	1	276	235	303		373	320	407	
	2	X	258	295		382	296	386	
	Avg.		246	299		378	308	396	
G	1	277	217	320		363	288	408	
	2	280	227	308		367	327	420	
	Avg.	278	222	314		365	308	414	
H	1	273	213	302		X	X	388	
	2	273	210	X		X	290	X	
	Avg.	273	212						
I	1	X	228	X		352	285	373	
	2	X	X	X		353	323	X	
	Avg.					352	304		
J	1	297	238	326		369	319	372	
	2	276	250	329		356	332	394	
	Avg.	286	244	328		362	326	383	
L	1	295	233	305		381	325	408	
	2	X	212	308		361	298	408	
	Avg.		222	306		371	312	408	
M	1	285	X	329		391	317	412	
	2	295	236	336		403	X	432	
	Avg.	290		332		397		422	
Grand Avg. ($\bar{X}$)		288	232	315	278	373	312	405	363
St. Dev. (σ)		13	13	16	14	19	16	19	18
Coeff. of Var. (V)		4.7	5.7	5.1	5.2	5.0	5.1	4.7	4.9



CONTROL CHART FOR AVERAGE ($\bar{X}$) & RANGE (R) OF TENSILE STRENGTH TESTS FOR CEMENT NUMBER 1 AT 3 DAYS

Differences Between Hand Mixed and Machine Mixed Mortars

In considering the effect of machine mixing on tensile strength as shown by the data, the overall picture may be viewed somewhat as follows:

Average of All Tests at 3 Days

Cement	1	2	3	Avg.
Hand Mixed	276	235	311	274
Machine Mixed	283	231	319	277
Machine Mixed	+7	-4	+8	+3

Average of All Tests at 7 Days

Cement	1	2	3	Avg.
Hand Mixed	362	320	381	354
Machine Mixed	373	316	405	364
Machine Mixed	+11	-4	+24	+10

Average of All Tests in Control at 3 Days

Hand Mixed	279	240	313	277
Machine Mixed	288	232	315	278
Machine Mixed	+9	-8	+2	+1

Average of All Tests in Control at 7 Days

Hand Mixed	356	314	388	353
Machine Mixed	373	312	405	363
Machine Mixed	+17	-2	+17	+10

In attempting a statistical evaluation of the significance of the differences observed between machine mixed and hand mixed batches, we may compare the averages of the results by means of the "t" test.

Using this test which is described in nearly all statistical texts, (5) the "significance ratio", or "Student's t" is computed from the data. This ratio is then compared with a tabulation of the critical t values. Tables of critical t values may also be obtained from any modern statistical text. If the computed t ratio is larger than the critical tabulated 5 percent value, the difference between the two sets of data is termed "significant". If the computed t value is larger than the critical tabulated 1 percent value, the difference is called "highly significant". A t value less than the critical 5 percent value is not significant.

Table 6 shows the results of these computations from the data of the tests which are in control limits.

Table 6

Results of Computation of t Values for Differences Between Hand Mixed and Machine Mixed Mortars

Cement Number	Age, Days	Average Values Hand Mixed	Average Values Machine Mixed	Computed t Values	Critical t Values 5%	Critical t Values 1%	Significance
1	3	279	288	1.96	2.030	2.724	Not significant
2	3	240	232	2.12	2.030	2.724	Significant
3	3	313	315	0.46	2.030	2.724	Not significant
1	7	356	373	3.37	2.030	2.724	Highly significant
2	7	314	312	0.41	2.021	2.704	Not significant
3	7	388	405	2.75	2.030	2.724	Highly significant

In considering the confidence to be placed in the statistics that may be computed from measurement data, they are as all laboratory workers know, only as good as the data. They are moreover, simply an expression of the probability that a given hypothesis is correct and it is necessary for any investigator to decide for himself the degree of probability that he is willing to accept. Normally this will depend upon two things; the consequences of drawing a certain type of erroneous conclusion called "an error of the first kind", and on taking the chance of "an error of the second kind". These concepts are discussed in nearly all statistical texts. In most cases a significance level of 5 percent or 1 percent is acceptable.

A statistical analysis is of course, no guarantee that a given conclusion is undubitably correct even though the computed probability is high. Statistical techniques do however, have one great advantage, and it is this. They are the best and most rational methods we have for the analysis of such data, and by using them it is possible to proceed systematically, and to arrive at an objective judgment of the significance of the test results.

Tables 7 and 8 show the results of the computations for repeatability and reproducibility. The last item in Table 8 shows the average results of the compressive strength tests for comparison. These compressive strength tests will be discussed later in this report.

Table 7

Repeatability and Reproducibility of Tensile Strength Tests on Portland Cement by Twelve Laboratories

ASTM Designation C 190

	Cement 1	Cement 2	Cement 3
Tensile Strength at 3 Days - All Tests Included			
Repeatability-Absolute	53.4	39.2	66.2
Repeatability-Percent of Average	19.3	16.7	21.4
Reproducibility-Absolute	83.2	49.2	102.8
Reproducibility-Percent of Average	30.1	20.9	33.2
Tensile Strength at 7 Days - All Tests Included			
Repeatability-Absolute	47.4	47.4	65.0
Repeatability-Percent of Average	13.1	14.8	17.0
Reproducibility-Absolute	83.8	71.8	93.5
Reproducibility-Percent of Average	23.1	22.4	24.4
Tensile Strength at 3 Days - Tests in Control			
Repeatability-Absolute	50.9	43.2	69.2
Repeatability-Percent of Average	18.2	18.1	22.1
Reproducibility-Absolute	53.2	26.7	51.1
Reproducibility-Percent of Average	19.1	11.1	16.3
Tensile Strength at 7 Days - Tests in Control			
Repeatability-Absolute	44.9	47.8	62.9
Repeatability-Percent of Average	12.6	15.2	16.2
Reproducibility-Absolute	38.6	34.7	57.6
Reproducibility-Percent of Average	10.9	11.0	14.8

Table 7
(Continued)

Repeatability and Reproducibility of
Tensile Strength Tests on Portland Cement
by Twelve Laboratories

ASTM Designation C 190

Machine Mixed Batches

	Cement		
	1	2	3
Tensile Strength at 3 Days - All Tests Included			
Repeatability-Absolute	48.0	48.0	50.0
Repeatability-Percent of Average	17.0	20.8	15.7
Reproducibility-Absolute	65.6	57.4	76.2
Reproducibility-Percent of Average	23.2	24.8	23.9
Tensile Strength at 7 Days - All Tests Included			
Repeatability-Absolute	70.1	54.5	60.5
Repeatability-Percent of Average	18.8	17.2	14.9
Reproducibility-Absolute	74.1	54.2	74.4
Reproducibility-Percent of Average	19.9	17.2	18.4
Tensile Strength at 3 Days - Tests in Control			
Repeatability-Absolute	47.4	49.2	49.8
Repeatability-Percent of Average	16.5	21.2	15.8
Reproducibility-Absolute	40.2	39.2	48.5
Reproducibility-Percent of Average	14.0	16.9	15.4
Tensile Strength at 7 Days - Tests in Control			
Repeatability-Absolute	72.1	47.5	62.1
Repeatability-Percent of Average	19.3	15.2	15.3
Reproducibility-Absolute	55.6	46.3	56.5
Reproducibility-Percent of Average	14.9	14.8	13.9

Table 8

Tensile Strength

Hand Mixed	3 Days All Tests	3 Days Cntrolld. Tests	7 Days All Tests	7 Days Cntrolld. Tests
Grand Average:				
Repeatability-% of Average	19.1	19.5	15.0	14.7
Reproducibility-% of Average	28.1	15.5	23.3	12.2
Machine Mixed				
Grand Average:				
Repeatability-% of Average	17.8	17.8	17.0	16.6
Reproducibility-% of Average	24.0	15.4	18.5	14.5

All Tests	Hand Mixed	Machine Mixed
Grand Average:		
Repeatability-% of Average	17.0	17.4
Reproducibility-% of Average	25.7	21.2

Compressive Strength C109

Machine Mixed	3 Days All Tests	3 Days Cntrolld. Tests	7 Days All Tests	7 Days Cntrolld. Tests
Grand Average:				
Repeatability-% of Average	9.1	8.4	8.0	7.1
Reproducibility-% of Average	22.8	8.3	25.4	8.7

Conclusions with Respect to the Tensile Strength Tests

1. The data of the tensile strength test indicates that none of the co-operating laboratories were able to perform the test without one or more of the observations being outside of the control limits. This is as heretofore noted, evidence of the presence of assignable causes of variation which must be located and removed before the testing procedure can be considered to be reliable. A larger number of subgroups of tests could conceivably change the picture to some extent, but it is probable that any test series in which a substantial number of laboratories test a reasonably large number of samples will show the same thing.

2. The precision of the tensile strength test as shown by the coefficient of variation is approximately 5 percent for the results that are within control limits.

3. There may be a real difference between the results of tensile strength tests obtained from machine mixed or hand mixed mortars. Different cements may not be affected in the same manner by the method of mixing and the method of mixing may or may not be significant at all ages.

4. With respect to the merits of machine mixing of tensile strength mortar, the analysis appears to indicate that when out-of-control results are eliminated, it has no advantage over hand mixing with respect to repeatability and reproducibility. When all of the reported test results are included, machine mixing appears to give slightly better reproducibility than hand mixing.

5. The test for compressive strength is shown to be far superior to the tensile test with respect to repeatability and also to reproducibility when out-of-control results are eliminated.

Analysis of the Compressive Strength Tests

The complete results of the compressive strength tests are shown in Table VIII. The results of the statistical analysis of the data are given below.

The results of the computations for control limits are given in Table 9, and the results of the computations for repeatability and reproducibility are shown in Table 10.

The amount of water used in the several mortars was designated by the California Division of Highways and each laboratory used the same amount with a given cement.

Table 9

Computed Control Limits for Averages ($\bar{X}$) Ranges (R) for Compressive Strength Tests

Cement Number	Age, Days	Grand Average $\bar{\bar{X}}$	Average Range $\bar{R}$	Computed Control Limits: Average $\bar{X}$ UCL*	Computed Control Limits: Average $\bar{X}$ LCL**	Computed Control Limits: Range R UCL	Computed Control Limits: Range R LCL
1	3	1666.3	59.4	1727.1	1605.5	153.0	0
2	3	1607.6	85.8	1695.4	1519.8	195.2	0
3	3	2073.9	120.2	2196.9	1950.9	309.5	0
1	7	2603.4	98.7	2704.4	2502.4	254.2	0
2	7	2495.0	121.0	2618.8	2371.2	311.6	0
3	7	3072.1	140.9	3216.2	2928.0	362.8	0

* Upper control limits

** Lower control limits

Table 10

Repeatability and Reproducibility of Compressive Strength Tests

All Tests

Age, Days		Cement Number 1	2	3
3	Repeatability Standard Deviation	36.8	56.1	80.3
3	Repeatability - Absolute	104.5	159.3	228.1
3	Repeatability - Percent of Average	6.3	9.9	11.0
3	Reproducibility Standard Deviation	137.0	126.0	154.6
3	Reproducibility - Absolute	398.7	366.7	449.9
3	Reproducibility - Percent of Average	23.9	22.8	21.7
7	Repeatability Standard Deviation	64.1	73.5	91.9
7	Repeatability - Absolute	182.0	208.7	261.0
7	Repeatability - Percent of Average	7.0	8.4	8.5
7	Reproducibility Standard Deviation	220.7	254.5	231.5
7	Reprodubility - Absolute	642.2	740.6	673.7
7	Reproducibility-Percent of Average	24.7	29.7	21.9

Tests in Control

Age, Days		Cement Number 1	2	3
3	Repeatability Standard Deviation	35.7	48.7	71.9
3	Repeatability-Absolute	106.0	142.2	207.8
3	Repeatability-Percent of Average	6.3	8.9	10.0
3	Reproducibility Standard Deviation	32.5	46.5	65.4
3	Reproducibility-Absolute	106.0	144.6	198.2
3	Reproducibility-Percent of Average	6.3	9.1	9.6
7	Repeatability Standard Deviation	51.7	65.4	78.8
7	Repeatability-Absolute	151.5	201.4	228.5
7	Repeatability-Percent of Average	5.8	8.0	7.4
7	Reproducibility Standard Deviation	49.8	85.4	80.5
7	Reproducibility-Absolute	156.9	310.9	245.5
7	Reproducibility-Percent of Average	6.0	12.3	7.9

Conclusions with Respect to the Compressive Strength Test

1. A substantial number of the laboratories were out of control limits on the compressive strength test as shown by the data in Table VIII.

2. The compressive strength test is superior to the tensile strength test with respect to repeatability and also to reproducibility when out-of-control tests are eliminated.

Analysis of the Autoclave Tests

The complete results of the autoclave test are shown in Table X. The results of the statistical analysis of these data are given below. The amount of water used in fabricating the test specimens was designated by the California Division of Highways.

Table 11 is a tabulation of the results and shows averages, maximum and minimum values, and ranges. Table 12 is a record of these same values for the tests that were in statistical control and also shows the computed control limits. Table 13 shows the results of the computations for repeatability and reproducibility.

In this series of tests, it is again observed that a substantial number of the tests are out of control. As a confirmation of the theory that control limits indicate assignable causes of variation, it is of interest to compare two analyses of variance of the data. One of the analyses was made on all of the reported values and clearly indicates that there were assignable causes of variation other than that produced by the differences in the three samples of cement. The analysis of the variance of the results that were in control limits, shows that the only significant cause of variation in this case was produced by the difference in the cements. These two analyses are shown in Tables 14 and 15.

Supplementary Observations on the Effect of Pressure

The method of test for the autoclave expansion of cement permits an autoclave pressure of 295 psi plus or minus 10 psi. All autoclaves are equipped with thermostatic controls, and the pressure during the 3 hours duration of the test is constantly varying between high and low, but within the prescribed limits. In this series of tests, the co-operating laboratories were asked to report the indicated gage pressure as the average of 12 readings at 15 minute intervals, starting 15 minutes after pressures reached 295 psi. These reported observations varied from 286 psi to 304 psi. This supplement reports an attempt to evaluate the effect of pressure on the length changes of the specimens by testing for a correlation between them.

The correlations found are linear, between 286 psi and 304 psi only, and were calculated by the method of least squares. The computed correlation data is shown below.

Correlation Data for Pressure and Length Changes

Cement Number	Regression Equation	Standard Error of Estimate Sy	Coefficient of Correlation (r)	Critical r	
				5%	1%
1	Y=0.2209-0.0006586 X	0.0046	0.492	0.406	0.517
2	Y=0.4086-0.0013991 X	0.0098	0.452	0.406	0.517
3	Y=0.5534-0.0011239 X	0.0158	0.267	0.406	0.517

X = Pressure in psi
Y = Length change in percent

The equations state that expansion decreases with increasing pressure. This is a surprising result and one that is contrary to the generally accepted rule of behavior. The coefficient of correlation for cements 1 and 2 is significant but not highly significant. The coefficient for cement 3 is not significant. The numerical value of the change in expansion with pressure within the limits of the specification tolerance is not large and is of no practical consequence for cements 1 and 2. It is possible that had a greater number of test results been available for study, the indicated trend would have been reversed.

Table 11

Results of the Autoclave Test on Three Cements
by Twelve Laboratories
Length Changes in Percent

Laboratory	Test Number	Cement Number 1 Indvdl.	Cement Number 1 Average	Cement Number 2 Indvdl.	Cement Number 2 Average	Cement Number 3 Indvdl.	Cement Number 3 Average
A	1	.025		-.005		.197	
	2	.033	.0290	.000	-.0025	.221	.2090
B	1	.031		.004		.235	
	2	.024	.0275	.000	.0020	.246	.2405
C	1	.033		-.002		.234	
	2	.036	.0345	-.005	-.0035	.220	.2270
D	1	.016		-.020		.221	
	2	.020	.0180	-.023	-.0215	.219	.2200
E	1	.026		-.006		.212	
	2	.035	.0305	.006	.0000	.250	.2310
F	1	.030		.010		.210	
	2	.030	.0300	.001	.0010	.210	.2100
G	1	.027		.012		.198	
	2	.029	.0280	.008	.0100	.190	.1940
H	1	.020		-.017		.233	
	2	.020	.0200	-.029	-.0230	.200	.2165
I	1	.028		.002		.214	
	2	.024	.0260	.009	.0055	.232	.2230
J	1	.020		-.010		.220	
	2	.020	.0200	-.010	-.0100	.230	.2250
L	1	.027		-.008		.222	
	2	.026	.0265	-.008	-.0080	.222	.2220
M	1	.026		-.013		.240	
	2	.022	.0240	-.020	-.0165	.234	.2370
Average		.0262	.0262	-.0052	-.0055	.2212	.2212
Highest Value		.0360	.0345	+.0120	+.0100	.2500	.2405
Lowest Value		.0160	.0180	-.0290	-.0230	.1900	.1940
Range		.0200	.0165	.0410	.0330	.0600	.0465

Table 12

Autoclave Tests on Three Cements by
Twelve Laboratories which are within Control Limits

Laboratory	Test Number	Cement Number 1 Indvdl.	Cement Number 1 Average	Cement Number 2 Indvdl.	Cement Number 2 Average	Cement Number 3 Indvdl.	Cement Number 3 Average
A	1	.025		-.005		.197	
	2	.033	.0290	.000	-.0025	.221	.2090
B	1	.031		.004		.235	
	2	.024	.0275	.000	.0020	.246	.2405
C	1	X		-.002		.234	
	2	X		-.005	-.0035	.220	.2270
D	1	X		X		.221	
	2	X		X		.219	.2200
E	1	.026		-.006		.212	
	2	.035	.0305	.006	.0000	.250	.2310
F	1	.030		X		.210	
	2	.030	.0300	X		.210	.2100
G	1	.027		X		X	
	2	.029	.0280	X		X	
H	1	X		X		.233	
	2	X		X		.200	.2165
I	1	.028		X		.214	
	2	.024	.0260	X		.232	.2230
J	1	X		-.010		.220	
	2	X		-.010	-.0100	.230	.2250
L	1	.027		-.008		.222	
	2	.026	.0265	-.008	-.0080	.222	.2220
M	1	.026		X		.240	
	2	.022	.0240	X		.234	.2370
Average		.0277		-.0037		.2237	
Highest Value		.0350		+.0060		.2500	
Lowest Value		.0220		-.0100		.2000	
Range		.0130		.0160		.0500	
UCL $\bar{X}$			.0352		+.0038		.2504
LCL $\bar{X}$			.0202		-.0112		.1970
UCL R			.0131		.0131		.0464
LCL R			0		0		0

Table 13

Repeatability and Reproducibility of Autoclave Tests on Three Cements by Twelve Laboratories

All Test Results Included in Computations

	Cements		
	1	2	3
Repeatability Standard Deviation	0.00319	0.00475	0.01284
Repeatability - Absolute	0.00992	0.01477	0.03993
Repeatability-Percent of Avg. Value	37.9	284.0	18.0
Reproducibility Standard Deviation	0.00490	0.01050	0.01282
Reproducibility - Absolute	0.01524	0.03265	0.03987
Reproducibility-Percent of Avg. Value	58.2	593.7	18.0
Average Length Change	0.0262	-0.0052	0.2212

Repeatability and Reproducibility of Autoclave Tests on Three Cements
All Out-of-Control Values Eliminated Before Computations of Values Given in the Table

	Cements		
	1	2	3
Repeatability Standard Deviation	0.00370	0.00402	0.01329
Repeatability - Absolute	0.01236	0.01463	0.04186
Repeatability-Percent of Avg. Value	44.6	395.4	18.7
Reproducibility Standard Deviation	0.00217	0.00460	0.00998
Reproducibility - Absolute	0.00725	0.01674	0.03145
Reproducibility-Percent of Avg. Value	26.2	452.4	14.1
Average Length Change	0.0277	-0.0037	0.2237

Table 14

Analysis of Variance of the Data in Table 11

Source of Variance	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	Critical F Ratio	
					5%	1%
Between Cements	0.72243	2	0.36122**	9030	3.40	5.61
Between Laboratories	0.00217	11	0.00020**	5.0	2.22	3.09
Between Tests	0.00001	1	0.00001	0.25	4.26	7.82
Cements X Laboratories	0.00455	22	0.00021**	5.0	2.05	2.79
Laboratories X Tests	0.00133	11	0.00012*	3.0	2.22	3.09
Residual	0.00104	24	0.00004			
Total	0.73153	71				

The interaction Cements X Tests was not significant, and its sum of squares, and mean square, are therefore, pooled with the residual sum of squares in the above table.

**Highly significant
*Significant

Table 15

Analysis of Variance Using Values
Given in Table 12

Source of Variance	Sum of Squares	Degrees of Freedom	Mean Squares	Computed F	Critical F 5%	Critical F 1%
Between Cements	.36069	2	.18034	2254	3.35	5.49
Between Laboratories	.00072	5	.00014	1.75	2.57	3.79
Between Tests	.00033	1	.00033	4.12	4.21	7.68
Residual	.00208	27	.00008			
Total	.36382	35				

Note: All interactions are non-significant and their mean squares are therefore pooled with residual mean squares.

Conclusions With Respect to the Autoclave Tests

1. The autoclave expansion of cements 1 and 2 is very low and the limits of accuracy obtained in the tests of them is of academic interest only.

   Cement 3 has a higher autoclave expansion. The analysis shows that repeatability is about 0.04 percentage points with or without the elimination of results that are out of control. Reproducibility is shown to be about 0.04 percentage points when all results are included. It is reduced to 0.03 when out-of-control results are eliminated. In terms of the average test result, the reproducibility is 14 percent.

2. The reproducibility for a cement having an autoclave expansion of 0.50 percent (the specification limit) is a point of major interest. The data do not afford a good basis for estimating its value. If it should prove to be similar to that found for cement 3, that is about 14 percent, its absolute value would be 0.07 percentage points.

Recommendation for Future Work

If co-operative testing for autoclave expansion is planned in the future, it is believed that more significant results would be obtained if each laboratory were to make about four independent tests on different days on each cement. The cements should be selected to afford a range in expansion with at least one near the specified maximum of 0.50 percent.

Results of the Chemical Analyses for Na_2O and K_2O and Statistical Analysis of the Data

The determination of Na_2O and K_2O in portland cement is of more than ordinary interest to the California Division of Highways and to the cement manufacturers who furnish the product for State Highway projects. This is because the alkali content of the cement is rigidly restricted to not more than 0.6 percent by the State specification requirements.

Because of the importance of these tests, the Materials and Research Department of the Division of Highways made a supplementary series of tests in addition to the tests performed in the co-operative series which is the subject of this report. In this section both series of tests will be discussed. Laboratories D and F did not participate in the co-operative tests for alkalies.

The results of all of the tests are shown in Tables XXVI and XXVII. Table 16 is a tabulation showing a number of statistical measures appertaining to the data; Table 17 shows the computed repeatability and reproducibility of the tests, and Table 18 is a compilation showing the tests and laboratories within computed control limits.

It was clearly evident from the data in the tables that reproducibility between laboratories in the determination of Na_2O and K_2O was not good unless steps were taken to eliminate results that were out of control. Since each laboratory made only two determinations, the validity of the computed control limits may be somewhat doubtful. It is also believed to be desirable to investigate the probability that the samples as distributed to the laboratories were in fact not alike.

In order to obtain further information as to possible causes of variance between laboratories, the California Division of Highways made further tests of four samples of Cement No. 1 that had been prepared at the same time as the remainder but had not been distributed. For purposes of identification in this report the four samples are designated A, B, C and D.

The program followed in this investigation was to make four independent determinations for Na_2O and K_2O of each sample on each of five days. Thus 80 determinations of Na_2O and K_2O were made in all. In these tests the Beckman DU spectrophotometer rather than the flame photometer specified in ASTM Designation C 114-51 T was used.

Table 16

Sodium Oxide and Potassium Oxide in Portland Cement
by Flame Photometer
ASTM Designation: C228-49T
Cements are Designated by the Number 1, 2, 3

Lab	Test No.	Na_2O			K_2O			Na_2O+.658 K_2O		
		1	2	3	1	2	3	1	2	3
A	1	.42	.10	.56	.20	.13	.45	.55	.19	.86
	2	.41	.11	.56	.20	.13	.46	.54	.20	.86
B	1	.40	.12	.57	.18	.10	.45	.52	.19	.87
	2	.40	.12	.57	.18	.10	.45	.52	.19	.87
C	1	.42	.09	.54	.20	.12	.45	.55	.17	.84
	2	.40	.08	.54	.19	.12	.45	.53	.16	.84
E	1	.42	.13	.58	.18	.11	.48	.54	.20	.90
	2	.42	.13	.58	.19	.12	.47	.55	.21	.89
G	1	.41	.10	.54	.22	.14	.51	.55	.19	.88
	2	.42	.12	.54	.20	.12	.48	.55	.20	.86
H	1	.43	.10	.57	.21	.12	.49	.57	.18	.89
	2	.44	.10	.58	.21	.12	.49	.58	.18	.90
I	1	.43	.10	.58	.22	.13	.51	.57	.19	.92
	2	.42	.11	.57	.20	.12	.51	.55	.19	.91
J	1	.46	.11	.62	.21	.12	.49	.60	.18	.94
	2	.46	.11	.62	.21	.12	.50	.60	.19	.95
K	1	.43	.10	.60	.21	.13	.51	.57	.19	.94
	2	.41	.09	.58	.21	.12	.50	.55	.17	.91
L	1	.35	.05	.51	.19	.11	.48	.48	.12	.83
	2	.36	.08	.54	.21	.12	.51	.50	.16	.88
M	1	.39	.10	.53	.185	.11	.44	.51	.17	.82
	2	.40	.10	.525	.185	.11	.44	.52	.17	.81
Average		.41	.10	.56	.20	.12	.48	.55	.18	.88
Maximum		.46	.13	.62	.22	.14	.51	.60	.21	.95
Minimum		.35	.05	.51	.18	.10	.44	.48	.12	.81
Range		.11	.08	.11	.04	.04	.07	.12	.09	.14
Standard Deviation		.0261	.0180	.0289	.0127	.0098	.0255	.0300	.0193	.0391
Coefficient of Var.		6.4	18.0	5.2	6.4	8.2	5.3	5.5	10.7	4.4

Table 17

Repeatability and Reproducibility of Na_2O and K_2O Analyses

All Tests

	Na_2O Cement 1	Na_2O Cement 2	Na_2O Cement 3	K_2O Cement 1	K_2O Cement 2	K_2O Cement 3
Repeatability-Absolute	.023	.026	.025	.023	.018	.025
Repeatability-Percent of Average	5.7	25.2	4.4	11.7	14.9	5.2
Reproducibility-Absolute	.082	.054	.029	.037	.028	.079
Reproducibility-Percent of Avg.	19.9	53.0	5.2	18.5	23.5	16.6
Average Value	.414	.102	.564	.200	.119	.478

Tests in Control Limits

	Na_2O Cement 1	Na_2O Cement 2	Na_2O Cement 3	K_2O Cement 1	K_2O Cement 2	K_2O Cement 3
Repeatability-Absolute	.027	.021	.016	.027	.015	.020
Repeatability-Percent of Average	6.5	20.7	2.9	13.1	12.6	4.1
Reproducibility-Absolute	.028	.019	.029	.021	.017	.024
Reproducibility-Percent of Avg.	6.8	18.5	5.1	10.1	14.6	4.9
Average Value	.415	.104	.570	.206	.119	.487

All Tests

	Na_2O+.658 K_2O Cement No.1	Na_2O+.658 K_2O Cement No.3
Repeatability-Absolute	.028	.038
Repeatability-Percent of Average	5.1	4.3
Reproducibility-Absolute	.094	.122
Reproducibility-Percent of Avg.	17.3	13.8
Average Value	.546	.880

Tests in Control Limits

	Na_2O+.658 K_2O Cement No.1	Na_2O+.658 K_2O Cement No.3
Repeatability-Absolute	.033	.024
Repeatability-Percent of Average	6.1	2.8
Reproducibility-Absolute	.030	.063
Reproducibility-Percent of Avg.	5.5	7.2
Average Value	.550	.878

Table 18

Table Showing Laboratories and Tests Within Control Limits

X Indicates a Test in Control

Participating Laboratories	Na_2O Cement 1	2	3	K_2O Cement 1	2	3	Na_2O+.658 K_2O Cement 1	3
A	X	X	X	X			X	X
B	X		X					X
C	X			X	X		X	
E	X				X	X	X	X
G	X	X		X			X	X
H		X	X	X	X	X		X
I	X	X	X	X	X		X	
J		X		X	X	X		
K	X	X		X	X		X	
L				X	X			
M		X			X			

All determinations were made by the same analyst. A period of six weeks intervened between the first and second rounds. The remainder were completed in less than two weeks. The results of the tests are shown in Table 19(A) and Table 19(B).

An inspection of the data shows at once that the results for Na_2O in the first round were considerably higher than in any succeeding round. There is no known reason for the high results in the first round.

By means of control charts it was determined that all of the values obtained for Na_2O in the first round were out of control which means that the variation from the other determinations is due to assignable causes.

When Round 1 is omitted, a few of the remaining results are out of control but by a very small margin. When these results are eliminated the remainder are in control. It makes little difference in the examination to follow whether or not all of the results of Rounds 2 to 5 are included. All of the data are considered to be good for the reason that the numerical value of the results is low and determinations cannot be made beyond two significant figures.

However, since the control charts for all results in Rounds 2 to 5 inclusive indicate that there are assignable causes of variation, the results of an analysis of variance are of interest. A three factor analysis is shown in Table 21. The results show that there are at least four factors (three main factors and an interaction) that are contributing significantly to the observed variance. One of these factors is a difference in the samples themselves. The probable magnitude of variations in the individual samples distributed to the co-operating laboratories is discussed below.

The analysis of variance indicates that a significant difference exists between the amounts of Na_2O in the samples, and this is confirmed by the computations of the 95 percent confidence limits in Table I. If it is assumed that the varying amounts of Na_2O in the samples distributed approximate a normal distribution, and that the four samples tested in this study were representative of the universe of samples, the standard deviation of the average value of each of the samples can be computed. This value is 0.0082. The probable distribution of Na_2O in the universe of samples is as follows:

Average Na_2O	$\pm$ 0.0082	68 percent
Average Na_2O	$\pm$ 0.0164	95 percent
Average Na_2O	$\pm$ 0.0246	99.7 percent

Table 19(A)

Results of Analyses of Portland Cement for Na2O Using the Beckman DU Spectrophotometer

Smpl.	(Round) Day Tested	Na_2O Test Number 1	2	3	4	Avg.	(Round) Day Tested	K_2O Test Number 1	2	3	4	Avg.
A	2	0.45	0.44	0.44	0.44	0.442	1	0.47	0.48	0.47	0.47	0.472
	3	0.45	0.44	0.44	0.44	0.442						
	4	0.42	0.43	0.42	0.42	0.422						
	5	0.42	0.41	0.42	0.42	0.418						
	Avg.	0.435	0.430	0.430	0.430	0.431	Avg.					0.472
	Standard Deviation					0.0126	Standard Deviation					0.0052
	Standard error of mean					0.0032	Standard error of mean					0.0026
	95% confidence limits:					0.438 0.424	95% confidence limits:					0.481 0.464
B	2	0.46	0.45	0.45	0.45	0.452	1	0.47	0.47	0.47	0.48	0.472
	3	0.45	0.43	0.45	0.43	0.440						
	4	0.43	0.43	0.42	0.42	0.425						
	5	0.44	0.46	0.45	0.45	0.450						
	Avg.	0.445	0.442	0.442	0.438	0.442	Avg.					0.472
	Standard Deviation					0.0132	Standard Deviation					0.0052
	Standard error of mean					0.0033	Standard error of mean					0.0026
	95% confidence limits:					0.449 0.435	95% confidence limits:					0.481 0.464
C	2	0.42	0.43	0.41	0.41	0.418	1	0.46	0.47	0.47	0.47	0.468
	3	0.44	0.46	0.43	0.43	0.440						
	4	0.42	0.42	0.43	0.42	0.422						
	5	0.45	0.45	0.43	0.44	0.442						
	Avg.	0.432	0.440	0.425	0.425	0.431	Avg.					0.468
	Standard Deviation					0.0143	Standard Deviation					0.0052
	Standard error of mean					0.0036	Standard error of mean					0.0026
	95% confidence limits:					0.438 0.423	95% confidence limits:					0.476 0.459
D	2	0.41	0.41	0.43	0.42	0.418	1	0.46	0.47	0.46	0.45	0.460
	3	0.42	0.43	0.41	0.41	0.418						
	4	0.46	0.43	0.43	0.42	0.435						
	5	0.43	0.43	0.41	0.41	0.420						
	Avg.	0.430	0.425	0.420	0.415	0.422	Avg.					0.460
	Standard deviation					0.0134	Standard Deviation					0.0141
	Standard error of mean					0.0033	Standard error of mean					0.0070
	95% confidence limits:					0.430 0.415	95% confidence limits:					0.482 0.438
	Grand Average, all tests					0.432	Grand Average, all tests					0.468
	Standard deviation, all tests					0.0148	Standard deviation, all tests					0.0075
	Standard error of mean					0.0018	Standard error of mean					0.0019
	95% confidence limits: 0.435,					0.428	95% confidence limits:					0.472 0.454
	Standard deviation, smpl. avgs.					0.0082	Standard deviation of sample averages					0.0063
	Standard deviation of all values in control					0.0127						

Table 19(B)

Results of Analyses of Portland Cement for K_2O Using the Beckman DU Spectrophotometer

Sample	Day Tested	K_2O Test Number 1	2	3	4	Avg.
A	1	0.21	0.21	0.20	0.19	0.202
	2	0.21	0.20	0.19	0.22	0.205
	3	0.21	0.20	0.20	0.21	0.205
	4	0.19	0.20	0.19	0.18	0.190
	5	0.20	0.19	0.19	0.20	0.195
	Avg.	0.204	0.200	0.194	0.200	0.200
	Standard deviation					0.0100
	Standard error of mean					0.0022
	95% confidence limits				0.204 and	0.195
B	1	0.22	0.20	0.21	0.19	0.205
	2	0.19	0.19	0.19	0.19	0.190
	3	0.21	0.21	0.21	0.20	0.208
	4	0.20	0.20	0.21	0.21	0.205
	5	0.20	0.21	0.19	0.20	0.200
	Avg.	0.204	0.202	0.202	0.198	0.201
	Standard deviation					0.0094
	Standard error of mean					0.0021
	95% confidence limits				0.206 and	0.196
C	1	0.21	0.20	0.19	0.19	0.198
	2	0.20	0.21	0.19	0.20	0.200
	3	0.22	0.22	0.21	0.21	0.215
	4	0.19	0.19	0.20	0.20	0.195
	5	0.20	0.20	0.19	0.20	0.198
	Avg.	0.204	0.204	0.196	0.200	0.201
	Standard deviation					0.0100
	Standard error of mean					0.0022
	95% confidence limits				0.206 and	0.196
D	1	0.21	0.21	0.19	0.19	0.200
	2	0.18	0.20	0.19	0.18	0.188
	3	0.20	0.21	0.19	0.20	0.200
	4	0.20	0.20	0.20	0.19	0.198
	5	0.20	0.19	0.20	0.20	0.198
	Avg.	0.198	0.202	0.194	0.192	0.196
	Standard deviation					0.0088
	Standard error of mean					0.0020
	95% confidence limits				0.201 and	0.192
	Grand Average, all tests					0.200
	Standard deviation, all tests					0.0095
	Standard error of mean					0.0011
	95% confidence limits				0.202 and	0.198
	Standard deviation of sample averages					0.0022

Table 20

Tabulation of the Data on Control Limits

Analysis	Test Included	$\bar{\bar{X}}$	$\bar{R}$	$UCL_{\bar{x}}$	$LCL_{\bar{x}}$	UCL_r	LCL_r
Na_2O	A1 to A5	0.4395	0.010	0.4468	0.4322	0.0228	0
"	B1 to B5	0.4480	0.014	0.4582	0.4378	0.0319	0
"	C1 to C5	0.4380	0.018	0.4511	0.4249	0.0411	0
"	D1 to D5	0.4300	0.024	0.4475	0.4125	0.0548	0
Na_2O	A2 to A5	0.4312	0.010	0.4385	0.4239	0.0228	0
"	B2 to B5	0.4419	0.015	0.4528	0.4310	0.0342	0
"	C2 to C5	0.4306	0.020	0.4452	0.4160	0.0456	0
"	D2 to D5	0.4225	0.025	0.4353	0.4097	0.0399	0
Na_2O	(A2-D5)	0.4316	0.0175	0.4444	0.4188	0.0399	0
Na_2O	(A2-D5)	0.4332	0.0180	0.4463	0.4201	0.0411	0

Table 21

Analysis of Variance of the Data Reported in Rounds 2 to 5

Source of Variance	Sums of Squares	D.F.	Mean Squares	F Ratio	Critical F 5%	Critical F 1%
Between Days Tested (Rounds)	0.00066	3	0.00022	3.14*	2.81	4.24
Between Samples	0.00303	3	0.00101	14.42*	2.81	4.24
Between Test Numbers	0.00081	3	0.00027	3.86*	2.81	4.24
Days Tested X smpls. (Interaction)	0.00600	9	0.00067	9.57*	2.09	2.82
Residual	0.00334	45	0.00007	----		
Total	0.01384	63				

*Indicates that the source of variance is significant.

The possibility exists therefore, that among the 13 samples distributed to the co-operating laboratories, two may have differed by as much as 0.05. It is more probable that the extreme difference was less than 0.02.

The evidence confirms that of the analysis of variance, namely, that the individual samples as prepared were not exactly alike and that part of the variance between laboratories was due to this cause.

It is apparent that precautions more extreme than those employed in the preparation of the samples of the 1956 co-operative series must be taken if variance in results due to non-uniformity of samples is to be avoided.

Each laboratory is concerned with the problem of determining at intervals whether its results are in control. The data of this report indicate that at least 20 tests preferably spaced over an interval of several days, should be made on the same sample and the results analyzed for statistical control. It is obvious that the sample selected for test should be prepared carefully to obtain as high a degree of uniformity as possible. If such a schedule were followed by all laboratories, it is believed that reproducibility would be improved substantially. The data of Rounds 2 to 5 inclusive afford a means of evaluating the precision of the determination of Na_2O since all of the results are in control or nearly so. The statistical measures of precision have already been defined in previous paragraphs.

The precision of a single measurement of Na_2O using the data of Rounds 2 to 5 is 0.0148 and the corresponding coefficient of variation is 3.43 percent. The precision using only those values in control is 0.0127 and the coefficient of variation is 2.93. The repeatability of the test is 0.0261 or 6.05 percent. These values may be compared with some others from the literature which are shown in the table below.

Na_2O

Method	Number of Determinations	Average Value	Standard Deviation	Coefficient of Variation
J. Lawrence Smith(6)	7	0.127	0.0170	13.38
	6	0.255	0.0138	5.41
	6	0.577	0.0383	6.63
	Average		0.0230	

Table continued on next page

Method	Number of Determinations	Average Value	Standard Deviation	Coefficient of Variation
		K_2O		
J. Lawrence Smith (6)	7	0.301	0.0147	4.88
	6	0.640	0.0110	1.72
	6	1.045	0.0164	1.57
	Average		0.0140	
		Na_2O		
Perkin-Elmer Model 52(7)	6	0.212	0.007	3.30
	6	0.618	0.015	2.43
	6	0.245	0.013	5.31
	6	0.375	0.017	4.53
	6	0.075	0.005	6.67
	Average		0.011	
		K_2O		
Perkin-Elmer Model 52(7)	6	0.508	0.023	4.53
	6	0.127	0.011	8.66
	6	0.222	0.007	3.15
	6	0.010	0.000	0.00
	6	0.257	0.011	4.28
	Average		0.010	
		Na_2O		
Beckman This report	64	0.432	0.0148	3.43
		K_2O		
Beckman This report	80	0.200	0.0095	4.74

It is believed that the precision of the method cannot be much improved over the precision found in these tests. What should be and probably can be improved, is the variation between laboratories.

The data for K_2O are much more concordant than those for Na_2O. Of the 20 subgroup averages for K_2O, only two were out of control and those in only small amounts. The precision calculated on the basis of all results is expressed as:

Standard deviation	0.0095
Coefficient of Variation	4.74 per cent

It is of interest now to compare the results obtained in the present tests with those obtained by all of the laboratories in the co-operative series. The comparison is summarized below.

Co-operative Tests

	Na_2O	K_2O
Average Value	0.414	0.200
Standard deviation (Between Laboratories)	0.026	0.013
Repeatability (Tests in Control)	0.027	0.027
Reproducibility (Tests in Control)	0.028	0.021

California Division of Highways

	Na_2O	K_2O
Averages for 4 Samples:		
All Rounds	0.439	0.200
Rounds 2 to 5	0.432	-----
Standard Deviation (Within one Laboratory)	0.0148	0.0095
Repeatability	0.026	0.023

It will be noted that the values for repeatability are nearly the same in both series. The values therefore, appear to be well established.

The fact that the standard deviation for all laboratories is much higher than that obtained in the California Division of Highways' supplementary tests appears to be merely a reflection of the known variance between laboratories as indicated by the reproducibility.

It will be noted that the average value for Na_2O obtained by the California Division of Highways in the supplementary series (excluding Round 1) is 0.018 higher than the average of all laboratories.

The Beckman DU spectrophotometer was used in the supplementary series and the Perkin-Elmer flame photometer in the co-operative series. Tests have since been made in the California Division of Highways laboratory to determine the probability of a difference in results between the two instruments. The original Sample 1 of the co-operative series assigned to the California Division of Highways was used for this purpose. The results are as follows:

	Na_2O		K_2O	
	Beckman	Perkin-Elmer	Beckman	Perkin Elmer
	0.43	0.42	0.20	0.20
	0.44	0.40	0.20	0.20
	0.42	0.41	0.19	0.21
	0.43	0.42	0.19	0.20
	0.44	0.42	0.20	0.20
Average	0.432	0.412	0.196	0.202

The average results are almost identical with those obtained in the supplementary tests and the original co-operative series respectively. The data therefore, confirm the indication that the Beckman instrument gives results for Na_2O that are higher than those obtained with the Perkin-Elmer instrument and that for cement No. 1, the differential is about 0.02 percentage point. The results of other investigators confirm this finding.(7)

Conclusions with Respect to the Chemical Analyses for Na_2O and K_2O

1. On the basis of the data provided by the co-operative series (one subgroup of two individuals from each laboratory), it was concluded that most of the laboratories were able to repeat their results rather closely. The reproducibility of the tests was not good.

   Since the determination of the alkali content was considered to be an important one, a supplemental series of tests was performed by the California Division of Highways. This supplemental series confirmed the values for repeatability as computed in the original series. The results also indicated that the samples as prepared for distribution to the co-operating laboratories were probably not identical in content of Na_2O.

2. A by-product of the investigation was that determinations for Na_2O with the Beckman instrument tend to be significantly higher than those obtained with the Perkin-Elmer instrument.

   Probably the most important finding was the need of individual laboratories to make sufficient repeat tests to permit establishing control limits so that results that are not in control can be eliminated. Unless this is done, it is idle to attempt to compute reproducibility between laboratories as a means of establishing tolerances in specification limits.

3. It was concluded that further work should be done on this test and it is anticipated that such work will be started in the fairly near future. It is also anticipated that future work will include alkali determinations on a standard sample in order that accuracy can be estimated as well as precision.

Analysis of the Tests for Fineness by the Turbidimeter and the Air Permeability Apparatus

The complete results of these tests are shown in Table III. Table 22 shows the computed control limits for two tests and Table 23 shows the results of the computations for repeatability and reproducibility.

Conclusions With Respect to the Turbidimeter and Air Permeability Tests

1. A larger proportion of the turbidimeter tests were in control limits than in the air permeability test. The repeatability and reproducibility of the air permeability results were considerably better than those obtained by the use of the turbidimeter.

Table 22

Computed Control Limits for Averages ($\overline{X}$) and Ranges (R) for the Fineness Tests

Cement Number	Grand Average $\overline{\overline{X}}$	Average Range $\overline{R}$	Computed Control Limits Average $\overline{X}$ UCL	Computed Control Limits Average $\overline{X}$ LCL	Range R UCL	Range R LCL
Turbidimeter Tests						
1	1549.6	19.5	1586.3	1512.9	63.8	0
2	1764.9	23.2	1808.5	1721.3	75.8	0
3	1895.4	22.4	1937.5	1853.3	73.2	0
Air Permeability Tests						
1	2795.8	14.1	2822.3	2769.3	46.1	0
2	2948.3	22.2	2990.0	2906.6	72.5	0
3	3820.2	17.0	3852.2	3788.2	55.5	0

Table 23

Repeatability and Reproducibility of the
Turbidimeter and Air Permeability Fineness Tests

All Tests

Turbidimeter Tests

	Cement Number		
	1	2	3
Repeatability - Absolute	47.7	61.1	58.8
Repeatability - Percent of Average	3.1	3.5	3.1
Reproducibility-Absolute	161.7	214.1	237.2
Reproducibility - Percent of Avg.	10.4	12.1	12.5
Air Permeability Tests			
Repeatability - Absolute	37.2	56.5	47.1
Repeatability - Percent of Average	1.3	1.9	1.2
Reproducibility-Absolute	149.7	165.4	359.7
Reproducibility-Percent of Average	5.4	5.6	9.4
Tests in Control			
Turbidimeter Tests			
Repeatability - Absolute	47.3	54.4	72.1
Repeatability - Percent of Average	3.0	3.1	3.8
Reproducibility-Absolute	78.9	70.1	101.6
Reproducibility-Percent of Average	5.1	4.0	5.3
Air Permeability Tests			
Repeatability - Absolute	30.1	60.8	19.8
Repeatability - Percent of Average	1.07	2.06	0.52
Reproducibility-Absolute	39.2	76.7	170.2
Reproducibility-Percent of Average	1.40	2.6	4.5

Analysis of the Tests for Time of Setting by Gillmore Needles

The results of these tests are shown in Table IV. Table 24 shows the computed control limits for the results of the test, and Table 25 is a record of the computations for repeatability and reproducibility. These latter computations were not made for the values that were within control limits on cements No. 2 and No. 3.

Conclusions with Respect to the Time of Setting Test

1. Approximately 42 percent of the determinations for initial and final set are out of control.
2. The repeatability and reproducibility calculated for the values in control on one cement are not good.

Table 24

Computed Control Limits for Averages ($\bar{X}$) and Ranges (R) for the Time of Setting by Gillmore Needles

Time in Minutes

Initial Set - All Tests

Cement Number	Grand Average $\bar{\bar{X}}$	Average Range R	Computed Control Limits: Average $\bar{X}$ UCL	Average $\bar{X}$ LCL	Range R UCL	Range R LCL
1	232.4	20.0	270.0	194.8	65.3	0
2	289.3	13.8	315.2	263.4	45.1	0
3	153.8	12.7	177.7	129.9	41.5	0
Final Set - All Tests						
1	377.6	23.5	421.8	333.4	76.8	0
2	451.2	19.5	487.9	414.5	63.7	0
3	284.9	19.4	321.4	248.4	63.4	0

Laboratories and Tests Within Control Limits

X Indicates a Test in Control

Laboratory	Initial Set Cement 1	Initial Set Cement 2	Initial Set Cement 3	Final Set Cement 1	Final Set Cement 2	Final Set Cement 3
A		X	X	X	X	X
B	X			X		
C	X		X		X	
D	X	X	X	X	X	
E				X	X	X
F	X			X		
G	X			X	X	
H	X	X	X		X	
I			X	X	X	X
J	X		X	X		X
K	X			X		X
L	X	X	X			
M	X		X	X	X	

Table 25

Repeatability and Reproducibility of the Time of Setting Tests by Gillmore Needles Time in Minutes

	Cement 1	Cement 2	Cement 3
All Tests - Initial Set			
Repeatability - Absolute	60.8	36.4	32.0
Repeatability - Percent of Average	26.2	12.6	20.8
Reproducibility - Absolute	97.3	122.0	75.1
Reproducibility - Percent of Average	41.9	42.2	48.9
All Tests - Final Set			
Repeatability - Absolute	60.0	50.6	56.4
Repeatability - Percent of Average	15.9	11.2	19.8
Reproducibility - Absolute	107.2	128.7	147.8
Reproducibility - Percent of Average	28.4	28.5	51.9
Tests in Control - Initial Set			
Repeatability - Absolute	49.6		
Repeatability - Percent of Average	21.5		
Reproducibility- Absolute	66.9		
Reproducibility - Percent of Average	29.0		
Tests in Control - Final Set			
Repeatability - Absolute	67.0		
Repeatability - Percent of Average	21.5		
Reproducibility - Absolute	74.9		
Reproducibility - Percent of Average	19.6		

The Normal Consistency Test

A complete record of the results of the normal consistency test is given in Table I. Each laboratory performed duplicate tests and nearly all the laboratories arrived at the same result for each of its own duplicate tests. It is easily seen that when little or no difference is observed between the members of a subgroup of tests conducted by two or more laboratories, but an appreciable difference exists between the averages of the subgroups tested by the different laboratories, an assignable cause of variation is present.

It is concluded from the data in Table I that assignable causes of variation are present to account for the observed differences in the results obtained by the several laboratories. The differences between some of them is so small however, as to seem to be negligible.

In connection with the above results, it is interesting to speculate about the results, if a larger number of tests were made, and precautions taken to prevent the entry of psychological bias in the experiments (8). In an experiment of this kind an operator would be furnished with about four samples per day for, say, 5 or 10 days. Suitable precautions would be taken to assure that the operator could not possibly know that the samples were duplicates. It is believed by some authorities that any chance for a psychological bias should always be eliminated where it is at all possible to do so.

In looking for an explanation of the observed differences, one of the most probable causes might be differences in room temperatures and relative humidites.

Penetration of Plunger C in a Paste Made with Percentage of Water Designated by the California Division of Highways

The results of this test are shown in Table II. There are obviously assignable causes for the variation observed. There are no data available to find out what these causes are.

Time of Setting by Vicat Needle

In this series of tests, the duplicate determinations were made on different days by all of the co-operating laboratories. The longest interval between duplicate tests was about 6 weeks, by laboratory M on all three tests. It will be observed that the difference between two of the duplicate tests (Cements 1 and 2) was the greatest reported by any of the laboratories. It is of interest to note however, that their results on Cement No. 3 were identical regardless of the time interval that apparently affected the behavior of the other two cements.

The only statistical computations made on these data are shown below. There were three laboratories out of control on Cement No. 1 and five laboratories out of control on Cement No. 2. Control limits were not computed for Cement No. 3. Table 26 is a record of the statistical computations made.

The amount of water used in this test was designated by the California Division of Highways.

Conclusions with Respect to the Time of Setting by Vicat Needle

1. This test has certain operational drawbacks which will work against its use in routine testing.

2. It is believed however, that this test could be brought into control limits without too much trouble, and that in this respect it would be superior to the Gillmore test. With regard to acceptance testing, and the limits now allowed in the Gillmore test, there seems to be no reason to be greatly concerned about its reliability or precision.

Table 26

Computed Control Limits for Averages ($\bar{X}$) and Ranges (R) for Time of Setting by Vicat Needle
Time in Minutes

All Tests

Cement Number	Grand Average $\bar{\bar{X}}$	Average Range $\bar{R}$	Computed Control Limits			
			Average $\bar{X}$		Range R	
			UCL	LCL	UCL	LCL
1	216.9	13.5	242.3	191.5	44.1	0
2	284.8	10.3	304.2	265.4	33.6	0

	Cement Number	
	1	2
Repeatability - Absolute	46.8	30.3
Repeatability - Percent of Average	21.6	10.6
Reproducibility - Absolute	72.4	114.9
Reproducibility - Percent of Average	33.4	40.4

Water Required for Flow of 108 Percent in C 109 Mortar

The results of this test are shown in Table IX. The differences in the amount of water used by the several laboratories in obtaining a flow of 108 percent in C109 mortar appears to be larger than can be accounted for except by assuming assignable causes of variation. The only remarks of any real value that can be made are that these causes of variation should be sought for and eliminated.

Air Content of Portland Cement

The results of this test are shown in Table XI. Here again it is observed that nearly all of the laboratories are able to obtain closely concordant duplicate results but that the average of the duplicate results vary widely from laboratory to laboratory. Here again, our conclusion must be that assignable causes of variation are operating and that they could probably be found and eliminated. The amount of water used in this test was designated by the California Division of Highways.

Water Required for Flow of 88 Percent in C 185 Mortar

The results of the tests are shown in Table XII. These results are somewhat similar to those obtained in the test for the amount of water required to obtain a flow of 108 on C109 mortar. In the case of the C109 mortar, the ratio of average range of all the tests to the grand average was:

$\frac{\bar{R}}{\bar{\bar{X}}}100 = 13.7$ and the like ratio for the results on the C185 mortar is

$$\frac{\bar{R}}{\bar{\bar{X}}}100 = 12.2$$

The tests were not performed in duplicate and no computations for control limits can therefore be made.

False Set of Portland Cement
ASTM Designation: C359-55T

The results of these tests are shown in Table XIII.

The results obtained by all of the laboratories on Cement No. 4, which is a cement that shows no sign of false set, are all practically identical.

The results obtained on Cement No. 5 are not good, with the exception that all laboratories were able to demonstrate that the false set was broken up by remixing. The results obtained on Cement No. 6 are very similar to those obtained on Cement No. 5.

This test as proposed is a tentative test. It does not state penetration values for deciding between a cement with false set and one without false set. From the results obtained by the laboratories at intervals of 5, 8, and 11 minutes it is apparent that the concordance between laboratories is very poor.

False Set of Portland Cement
Federal Specification SS-C-158c, 4.4.11

The results of these tests are shown in Table XIV.

All of the results by all of the laboratories classified Cement No. 4 as not showing false set. Cement No. 5 would be classified by seven of the thirteen laboratories as showing false set. It would not be so classified by six of the laboratories.

Eleven of the thirteen laboratories would classify Cement No. 6 as showing false set.

These results cannot be compared with the false set results by the ASTM method, since that method has no criteria as to what does or does not constitute false set.

False Set of Portland Cement
Test Method No. Calif. 503A

The results of these tests are shown in Table XV. Laboratory D, did not perform these tests.

In using this test procedure three of the laboratories would have considered Cement No. 4 as false setting, eleven of the twelve laboratories would have considered Cement No. 5 as showing false set and eleven of the twelve would also have considered Cement No. 6 to be in that category.

From the data it would be difficult to say with any certainty, which of the methods for false set (Federal or California) is superior.

Specific Gravity of Portland Cement

The results of these tests are shown in Table XVI.

It is apparent from a glance at the data that a considerable number of the results would be out of control. It is interesting to note that as long ago as 1919, W. F. Hillebrand(9) called attention to the care that is necessary in making a determination of specific gravity, to avoid an error of several points in the second place of decimals.

This test is usually not one of great importance, but it is apparent that the values in the second place of decimals are not too reliable.

Chemical Analysis of Portland Cement For Silicon Dioxide

The results of these tests are shown in Table XVII.

Table 27 shows the computed control limits and the laboratories and tests in control. Table 28 shows the repeatability and reproducibility of some of the results. These values were not computed for the values in control for cements No. 2 and No. 3.

In the determination of SiO_2, the maximum permissible variation between two results (10), presumably by the same operator is 0.16. It will be observed in Table XVII that four sets of tests failed to conform to this requirement. The average variation or range between the duplicate tests is 0.07. If this value is representative of what the average laboratory can do with this test, the control limits within which any individual laboratory or operator should work providing that the test method is reliable should be $\bar{X} \pm 0.13$ percent for $\bar{X}$ and from 0 to 0.23 for ranges when subgroups of two are used in the computations. If 0.07 is actually about the average range that laboratories will attain, it is possible to <u>estimate</u> the standard deviation of a universe of such tests. It is done by multiplying the average range by a constant depending upon the number of tests in each subgroup. For subgroups of two, the constant is $\frac{1}{d_2} = 0.8865$. The table of constants can be found in reference (1). In the present case the estimated universe standard deviation of the test wolld be (0.07)(0.8865)=0.062 percent.

Conclusions with Respect to the Analysis for SiO_2

1. A substantial number of the co-operating laboratories are out of control in this test.
2. Three laboratories failed in one or more tests to maintain the permissible variation between two duplicate tests.
3. An estimate of the universe standard deviation of the test as computed from the average of 25 pairs of results as

Conclusions with Respect to the Analysis for SiO_2 (Continued)

3. (Continued)

described above is $\sigma' = 0.062$ percent. For an average SiO_2 content of say 22.00 percent, this would work out as a coefficient of variation of $\frac{0.062}{22.00}$ 100 = 0.28 percent.

These values are estimates of the standard deviation of a normal universe, and are hence the estimation of the standard deviation of a test method that is in control.

Table 27

Computed Control Limits for Averages ($\bar{X}$) and Ranges (R) for Silicon Dioxide in Portland Cement

All Tests

Cement Number	Grand Average $\bar{\bar{X}}$	Average Range $\bar{R}$	Computed Control Limits			
			Average $\bar{X}$		Range R	
			UCL	LCL	UCL	LCL
1	22.88	.093	23.05	22.71	0.30	0
2	24.73	0.092	24.90	24.56	0.30	0
3	20.56	0.066	20.68	20.44	0.22	0

Laboratories and Tests Within Control Limits

X Indicates a test in Control

Laboratories	Cement		
	1	2	3
A	X		X
B	X	X	X
C	X	X	X
D	X	X	X
E			
F	X	X	X
G	X		
H			
I			
J	X	X	X
K	X	X	X
L	X		
M			

Table 28

Repeatability and Reproducibility of
Analyses for Silicon Dioxide

All Tests

	Cement Number		
	1	2	3
Repeatability - Absolute	0.276	0.223	0.154
Repeatability - Percent of Average	1.21	0.90	0.75
Reproducibility - Absolute	0.831	0.746	0.300
Reproducibility - Percent of Average	3.63	3.02	1.46
Tests in Control			
Repeatability - Absolute	0.174		
Repeatability - Percent of Average	0.76		
Reproducibility - Absolute	0.317		
Reproducibility - Percent of Average	1.39		

Chemical Analysis of Portland Cement for Aluminum Oxide

The results of these tests are shown in Table XVIII.

The maximum permissible variation between two results in the analysis for Al_2O_3 is 0.20. (10). Reference to Table XVIII indicates that this requirement has not been attained in three cases out of the thirty-nine tabulated. One laboratory was responsible for two failures. The average range of the remaining values was 0.08 percent.

Assuming that this $\bar{R}$ = 0.08 is representative of what an average laboratory can do, it is possible to estimate the standard deviation σ' and V' as was done in the test for SiO_2. In this case it is (0.08)(0.8865) = 0.071 percent and V' for an average Al_2O_3 content of 4 percent would be 1.77 percent.

Chemical Analysis of Portland Cement for Ferric Oxide

The results of these tests are shown in Table XIX. The maximum permissible variation between two results in the analysis for Fe_2O_3 is 0.10. As shown in Table XIX, none of the laboratories have failed to meet this requirement. The average difference or average range of all of the values is 0.02.

The estimated σ' = (0.02)(0.8865) = 0.018 percent and the estimated V' for an average Fe_2O_3 content of 3 percent would be 0.6 percent.

Chemical Analysis of Portland Cement for Calcium Oxide

The results of these tests are shown in Table XX.

The maximum permissible variation between two results is 0.20. Five of the thirty-nine duplicate tests failed to meet this requirement. The average difference or range of all of the other values is 0.09.

The estimated σ' is therefore 0.08 percent and the estimated coefficient of variation for an average CaO value of say 65.00 is 0.12 percent.

Chemical Analysis of Portland Cement for Magnesium Oxide

The results of these tests are shown in Table XXI.

The maximum permissible variation between two results is 0.16. Three of the thirty-nine tests failed to meet this requirement. The average difference or range of all the other values is 0.04 percent.

The estimated σ' is therefore 0.035 percent and the estimated V' for an average MgO value of 4 percent is 0.9 percent.

Chemical Analysis of Portland Cement for Loss on Ignition

The results of these tests are shown in Table XXII.

The maximum permissible variation between the results is 0.10. Three of the thirty-nine tests failed to meet the requirement.

The average range of the other values is 0.033 percent. The estimated standard deviation of the method (σ') is therefore, 0.029 percent.

Chemical Analysis of Portland Cement for Sulfur Trioxide

The results of these tests are shown in Table XXIV.

The maximum permissible variation between results is 0.10. All of the tests were within this tolerance.

The average range of all tests was 0.029 percent. The estimated standard deviation of the test (σ') was 0.026 percent.

Chemical Analysis of Portland Cement for Calcium Sulfate in Hydrated Portland Cement Mortar.

The results of these tests are shown in Table XXV.

The results of tests indicate that the individual laboratories are able to duplicate their results fairly closely, but that the results between laboratories are far from satisfactory. This confirms the results obtained from co-operative tests on this method in the past.

This method is no longer standard for acceptance testing.

Conclusions with Respect to All of the Tests

1. The foregoing series of co-operative test results affords convincing evidence that assignable causes of variation account for at least a substantial amount of the differences observed between the test results as reported by the co-operating laboratories. It is obvious that an effort should be made to locate and eliminate these causes.

2. In order to do so it is suggested that it is first necessary for each laboratory to accumulate evidence that all or any of the tests are reliable in the hands of its own operators.

3. If it can be shown that any particular test is not reliable in the hands of say, a majority of operators, some consideration should be given to a revision of such tests.

4. It is suggested that criteria based on recent statistical findings should be adopted for deciding upon the reliability of the test methods, and for future co-operative tests.

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Co-operative Tests of Portland Cement
Series of 1956

Table I

NORMAL CONSISTENCY of Three Portland Cements Designated 1, 2 and 3, by Thirteen Laboratories Designated A to M, According to A.S.T.M. Method Designation: C187-49

Laboratory Code	Test Number	Cement Number 1	2	3
A	1	24.0	21.6	24.0
	2	24.0	21.6	24.0
B	1	23.2	21.0	24.2
	2	23.2	21.0	24.2
C	1	24.8	22.6	24.6
	2	24.8	22.6	24.6
D	1	23.5	21.4	23.7
	2	23.5	21.4	23.7
E	1	23.0	21.2	23.0
	2	23.4	21.2	23.0
F	1	24.0	21.0	24.0
	2	24.2	21.0	24.2
G	1	24.0	22.0	23.9
	2	24.0	21.6	23.9
H	1	25.0	21.2	24.2
	2	25.0	21.2	24.2
I	1	23.8	21.4	23.6
	2	23.8	21.4	23.6
J	1	24.0	21.4	24.4
	2	24.0	21.4	24.4
K	1	24.6	21.2	24.6
	2	24.4	21.2	24.6
L	1	24.6	21.6	24.5
	2	24.4	21.6	24.5
M	1	24.6	21.2	24.2
	2	24.4	21.2	24.2
Average		24.1	21.4	24.1
Minimum		23.0	21.0	23.0
Maximum		25.0	22.6	24.6

Co-operative Tests of Portland Cement
Series of 1956

Table II

PENETRATION OF PLUNGER C
of A.S.T.M. C187-49 in Paste Made with
Percentage of Water Designated by California
Div. of Highways on Three Portland Cements Designated
1, 2, and 3 by Thirteen Laboratories
Designated A to M

Laboratory Code	Test Number	Cement Number 1	Cement Number 2	Cement Number 3
A	1	20	25	12
	2	22	26	13
B	1	28	29	15
	2	29	14	21
C	1	12	9	11
	2	10	9	10
D	1	38	29	25
	2	38	35	26
E	1	15	20	15
	2	20	25	21
F	1	13	21	12
	2	16	25	13
G	1	14	15	18
	2	18	17	19
H	1	7	22	12
	2	8	18	13
I	1	24	21	21
	2	23	20	21
J	1	15	29	12
	2	16	27	11
K	1	12	26	12
	2	9	19	11
L	1	11	23	13
	2	12	26	14
M	1	12	25	14
	2	15	22	14
Average		18	22	15
Minimum		7	9	10
Maximum		39	35	26

Table III

FINENESS
of Portland Cement by the Turbidimeter
A.S.T.M. Designation: C115-53
Fineness of Portland Cement by the Air Permeability Apparatus
A.S.T.M. Designation: C204-55
Three Cements Designated 1, 2 and 3, by Thirteen Laboratories
Designated A to M

Laboratory Code	Test Number	Turbidimeter			Air Apparatus		
		Cement Number			Cement Number		
		1	2	3	1	2	3
A	1 2	1586 1605 x	1800 1787	1943 1930	2822 2811	2978 2999	3805 3791
B	1 2	1556 1541	1754 1764	1775 1780 x	2753 2742 x	2908 2950	3746 3715 x
C	1 2	1587 1587 x	1864 1813 x	2000 1954 x	2783 2804	2954 2912	3806 3806
D	1 2	1455 1409 x	1744 1805	1878 1950	2790 2748 x	2949 2922	3642 3661 x
E	1 2	1489 1514 x	1774 1771	1894 1876	2731 2753 x	2908 2950	3828 3877 x
F	1 2	1570 1590	1790 1780	1950 1970 x	2890 2900 x	3000 3010 x	3910 3900 x
G	1 2	1560 1542	1765 1776	1883 1870	2805 2794	2950 2950	3850 3850
H	1 2	1618 1639 x	1875 1898 x	1874 1857	2869 2879 x	3054 3012 x	3893 3909 x
I	1 2	1533 1520	1727 1732	1820 1811 x	2757 2757 x	2906 2905 x	3750 3750 x
J	1 2	1484 1488 x	1686 1680 x	1844 1855 x	2842 2852 x	2974 2963	3911 3893 x
K	1 2	1575 1595	1800 1770	1910 1930	2802 2802	2950 2950	3779 3788 x
L	1 2	1575 1564	1767 1737	1813 1800 x	2880 2850 x	3001 2970	4105 4060 x
M	1 2	1575 1533	1590 1638 x	2074 2040 x	2740 2735 x	2805 2825 x	3645 3655 x
Average		1550	1765	1895	2796	2948	3820
% Tests in Control		53.8	69.2	46.2	30.8	69.2	23.1
Repeatability: Absolute Percent**		47.3 3.0	54.4 3.1	72.1 3.8	30.1 1.07	60.8 2.06	19.8 0.52
Reproducibility: Absolute Percent		78.9 5.1	70.1 4.0	101.6 5.3	39.2 1.40	76.7 2.6	170.2 4.5

** Based on tests in control

x Indicates tests out of control

Co-operative Tests of Portland Cement
Series of 1956

Table IV

TIME OF SETTING
of Hydraulic Cements by Gillmore Needles
A.S.T.M. Designation: C266-51T
Three Cements Designated 1, 2 and 3, by Thirteen Laboratories
Designated A to M

Laboratory Code	Test Number	Cement Number 1 Initial	1 Final	2 Initial	2 Final	3 Initial	3 Final
A	1	3:00	6:35	5:05	8:00	2:25	4:55
	2	3:00	6:25	5:10	8:05	2:35	5:05
B	1	3:55	6:40	4:05	8:25	2:00	3:55
	2	3:50	6:30	4:00	8:10	2:10	4:05
C	1	4:05	5:30	5:30	7:30	2:20	3:40
	2	3:45	5:30	5:20	6:45	2:25	3:35
D	1	4:00	7:00	4:45	7:30	3:00	6:00
	2	3:35	6:50	4:45	7:45	2:40	5:25
E	1	4:30	5:55	4:35	6:45	3:15	5:00
	2	3:15	5:15	3:55	7:40	3:05	5:05
F	1	4:10	6:05	5:40	8:55	3:05	5:20
	2	4:20	6:35	5:30	8:40	2:55	5:30
G	1	3:40	6:30	5:15	7:20	3:00	5:50
	2	3:50	6:35	5:35	7:30	3:15	6:00
H	1	3:39	7:03	4:40	7:22	2:50	6:16
	2	3:35	7:30	4:40	7:08	2:15	5:02
I	1	5:00	6:40	5:25	7:15	2:45	4:10
	2	5:10	6:05	5:40	7:30	2:55	4:35
J	1	3:25	6:17	3:55	8:46	2:10	5:01
	2	3:36	6:53	4:04	8:58	2:12	5:07
K	1	3:32	6:08	3:52	6:10	1:42	3:55
	2	3:06	5:31	3:27	6:22	2:05	4:32
L	1	3:50	5:20	4:40	6:15	2:40	3:55
	2	4:00	5:15	5:05	6:45	2:25	3:30
M	1	4:00	6:00	5:15	7:00	2:15	4:00
	2	5:00	7:00	5:30	7:00	2:15	4:00
Average		3:52	6:18	4:49	7:31	2:34	4:45
Minimum		3:00	5:15	3:27	6:10	1:42	3:30
Maximum		5:10	7:30	5:40	8:58	3:15	6:16

Co-Operative Tests of Portland Cement
Series of 1956

Table V

TIME OF SETTING of Hydraulic Cement by Vicat Needle
A.S.T.M. Designation: C191-52. Three Cements Designated
1, 2, and 3, by Thirteen Laboratories Designated A to M

Laboratory Code	Test Number	Cement No. 1	Cement No. 2	Cement No. 3
A	1	165	295	300
	2	160	295	305
B	1	200	200	120
	2	210	195	135
C	1	220	289	139
	2	222	277	124
D	1	210	255	120
	2	195	255	105
E	1	255	325	135
	2	260	335	130
F	1	205	265	145
	2	210	255	135
G	1	215	290	130
	2	240	295	135
H	1	195	288	123
	2	195	270	126
I	1	250	360	145
	2	230	345	155
J	1	232	301	115
	2	227	291	112
K	1	215	257	108
	2	218	282	127
L	1	225	295	125
	2	220	310	120
M	1	195	305	110
	2	270	275	110
Average		217	285	140
Minimum		160	195	105
Maximum		270	360	305

Co-Operative Tests of Portland Cement
Series of 1956

Table VI

Part 1

TENSILE STRENGTH of Hydraulic Cement Mortars
A.S.T.M. Designation: C190-49. Three Cements Designated
1, 2 and 3, by Twelve Laboratories Designated A to M

Laboratory Code	Test Number	Cement No. 1		Cement No. 2		Cement No. 3	
		3 Days	7 Days	3 Days	7 Days	3 Days	7 Days
A	1	265 270 270 268	340 355 355 350	235 240 245 240	300 300 320 307	290 325 305 307	385 400 375 387
	2	260 265 260 262	360 360 340 353	255 245 245 247	320 305 310 313	285 315 310 303	385 365 385 378
B	1	277 271 268 272	346 339 328 338	228 236 236 233	300 310 275 295	244 229 249x 241	349 348 304x 334
	2	274 270 266 270	348 347 340 345	234 238 237 236	315 302 298 305	238 247 230x 238	333 351 334x 339
C	1	300 310 285 298	377 392 416x 395	236 270 237 248	338 313 342 331	331 348 325 335	394 404 410 403
	2	280 313 314 302	364 396 371 377	253 238 244 245	329 364 360x 351	339 321 354 338	366 347 374 362
D	1	315 290 270 292	365 345 350 353	265 250 225 247	355 300 320 325	375 340 350x 355	365 455 395 405
	2	325 275 295 298	345 360 330 345	265 260 255x 260	315 325 320 320	320 300 360 327	375 395 400 390
E	1	305 295 300 300	410 390 420x 407	265 260 240 255	400 370 400x 390	320 330 350 333	410 440 415x 422
	2	315 290 280 295	370 400 350 373	260 210 205 225	295 340 300 312	350 310 305 322	370 385 435 397

Co-Operative Tests of Portland Cement
Series of 1956

Table VI

Part 2

TENSILE STRENGTH of Hydraulic Cement Mortars
A.S.T.M. Designation C190-49

Laboratory Code	Test Number	Cement No. 1 3 Days	Cement No. 1 7 Days	Cement No. 2 3 Days	Cement No. 2 7 Days	Cement No. 3 3 Days	Cement No. 3 7 Days
F	1	240 265 265 257	310 360 360 343	230 240 240 237	340 310 310 320	300 370 320 330	325 280 350x 318
	2	270 305 270 282	335 365 340 347	225 250 250 242	320 310 315 315	370 415 430x 405	425 435 385 415
G	1	260 250 275 262	380 375 405x 387	245 245 255 248	325 305 305 312	278 292 278 283	390 410 403 401
	2	250 260 235x 248	380 380 355 372	220 250 230 233	300 310 325 312	305 318 325 316	420 415 400 412
H	1	200 215 210x 208	305 290 290x 295	200 200 200x 200	265 260 285x 270	285 275 280 280	340 380 340 353
	2	235 285 275 265	340 350 345 345	245 225 230 233	295 300 300 297	325 335 285 315	380 370 400 383
I	1	190 255 270x 228	370 350 370 363	205 180 200x 195	310 310 275 298	255 280 320 285	315 320 350x 328
	2	280 255 250 262	380 345 365 363	210 210 210x 210	335 345 340 340	290 255 255x 267	345 380 355 363
J	1	256 285 245 262	386 370 373 376	225 211 217 218	315 323 270 303	347 277 295 306	360 391 330 360
	2	297 333 335x 322	354 335 337 342	216 234 275 242	320 301 341 321	289 282 340 304	425 388 411 408

Co-Operative Tests of Portland Cement
Series of 1956

Table VI

Part 3

TENSILE STRENGTH of Hydraulic Cement Mortars
A.S.T.M. Designation C190-49

Laboratory Code	Test Number	Cement No. 1		Cement No. 2		Cement No. 3	
		3 Days	7 Days	3 Days	7 Days	3 Days	7 Days
L	1	305 305 275 295	350 310 360 340	235 225 245 235	330 310 335 325	320 315 310 315	400 380 390 390
	2	255 260 255 257	375 375 355 366	215 205 220x 213	290 315 330 311	295 315 310 307	360 415 390 388
M	1	297 305 290 297	360 383 345 362	270 240 230 247	363 361 343x 356	343 290 293 309	420 425 430x 425
	2	325 341 335x 334	415 438 478x 444	258 231 250 246	350 343 356x 350	288 318 370 325	460 449 381x 430
Average		276	362	235	320	311	381
Per Cent of Tests in Control		58.3	58.3	58.3	58.3	58.3	41.7
Repeatability-Absolute		50.9	44.9	43.2	47.8	69.2	62.9
Repeatability %		18.2	12.6	18.1	15.2	22.1	16.2
Reproducibility-Absolute**		53.2	38.6	26.7	34.7	51.1	57.6
Reproducibility %		19.1	10.9	11.1	11.0	16.3	14.8

**Based on tests in control
x Indicates tests out of control
Laboratory K did not make these tests.

Co-Operative Tests of Portland Cement
Series of 1956

Table VII

Part 1

TENSILE STRENGTH of Hydraulic Cement Mortars
A.S.T.M. Designation: C190-49 and C305-53T. Machine Mixed

Laboratory Code	Test Number	Cement No. 1		Cement No. 2		Cement No. 3	
		3 Days	7 Days	3 Days	7 Days	3 Days	7 Days
A	1	315 295 310 307	395 380 410 395	245 240 245 243	320 320 310 317	350 340 340 343	430 395 400 408
	2	295 290 290 292	380 370 370 373	255 235 260 250	305 305 315 308	355 345 340x 347	410 410 415 411
B	1	313 299 296 303	410 393 408 404	211 188 195x 198	326 321 326 324	282 307 288 292	435 438 421 431
	2	314 311 309x 311	407 404 404 405	204 208 196x 203	312 318 326 319	291 290 300 294	427 432 435 431
C	1	303 299 323 308	447 413 384x 415	243 202 234 226	299 305 320 308	321 376 388x 362	420 464 449x 444
	2	300 322 315x 312	436 402 402x 413	209 250 228 229	339 327 320 329	363 348 333x 348	423 449 481x 451
D	1	270 300 295 288	360 365 380 368	240 270 200 237	280 380 340x 333	295 320 360 325	385 375 350 370
	2	315 315 295 308	355 310 350 338	235 230 225 230	310 350 340 333	330 330 325 328	400 460 375 412
E	1	290 305 300 298	370 380 370 373	250 220 245 238	320 325 275 307	360 350 350x 353	395 420 335 417
	2	290 240 265 265	350 385 340 358	250 280 255x 262	300 290 270 287	345 380 375x 367	430 405 420 418

Co-Operative Tests of Portland Cement
Series of 1956

Table VII

Part 2

TENSILE STRENGTH of Hydraulic Cement Mortars
A.S.T.M. Designation: C190-49 and C305-53T. Machine Mixed

Laboratory Code	Test Number	Cement No. 1		Cement No. 2		Cement No. 3	
		3 Days	7 Days	3 Days	7 Days	3 Days	7 Days
F	1	280 290 260x 276	365 375 380 373	220 245 240 235	330 330 300 320	335 290 285 303	370 410 440 407
	2	220 250 255 242	390 355 400 382	265 220 290 258	290 285 315 296	300 295 290 295	400 380 380 386
G	1	290 280 260 277	350 365 375 363	220 230 200 217	280 265 320 288	325 315 320 320	390 420 415 408
	2	285 270 285 280	375 380 345 367	215 230 235 227	320 345 315 327	305 315 305 308	420 415 425 420
H	1	260 265 295 273	335 325 310x 326	205 225 210 213	350 340 345x 345	275 305 325 302	375 405 385 388
	2	260 280 280 273	320 310 350 327	210 210 210 210	285 290 295 290	270 290 290x 284	350 360 345x 352
I	1	220 280 220x 240	420 345 290x 352	250 235 200 228	280 310 265 285	275 285 275x 278	385 380 355 373
	2	230 250 235 238	350 380 330 353	185 175 220x 193	305 345 320 323	285 300 255x 280	370 360 370x 367
J	1	256 322 314 297	398 350 360 369	234 258 223 238	336 296 325 319	318 350 311 326	342 380 393 372
	2	277 265 285 276	353 326 390 356	247 253 250 250	324 359 312 332	318 330 339 329	403 375 405 394

Co-Operative Tests of Portland Cement
Series of 1956

Table VII

Part 3

TENSILE STRENGTH of Hydraulic Cement Mortars
A.S.T.M. Designation: C190-49 and C305-53T. Machine Mixed

Laboratory Code	Test Number	Cement No. 1		Cement No. 2		Cement No. 3	
		3 Days	7 Days	3 Days	7 Days	3 Days	7 Days
L	1	275 275 315 288	395 370 380 381	240 230 230 233	340 320 315 325	320 305 290 305	425 400 400 408
	2	245 270 250x 255	350 375 360 361	215 215 205 212	285 320 290 298	280 320 325 308	375 420 430 408
M	1	293 265 297 285	406 426 340 391	259 263 285x 269	332 300 320 317	310 345 332 329	380 397 460 412
	2	280 307 297 295	368 428 412 403	225 238 244 236	347 375 340x 354	354 335 320 336	430 420 447 432
Average		283	373	231	316	319	405
Per Cent of Tests in Control		58.3	66.7	58.3	75.0	33.3	67.0
Repeatability-Absolute		47.4	72.1	49.2	47.5	49.8	62.1
Repeatability-%		16.5	19.3	21.2	15.2	15.8	15.3
Reproducibility-Absolute **		40.2	55.6	39.2	46.3	48.5	56.5
Reproducibility-%		14.0	14.9	16.9	14.8	15.4	13.9

** Based on tests in Control
x Indicates tests out of Control
Laboratory K did not make these tests.

Co-Operative Tests of Portland Cement
Series of 1956

Table VIII

Part 1

COMPRESSIVE STRENGTH of Hydraulic Cement Mortars
A.S.T.M. Designation: C109-54T

Laboratory Code	Test Number	Cement No. 1 3 Days	Cement No. 1 7 Days	Cement No. 2 3 Days	Cement No. 2 7 Days	Cement No. 3 3 Days	Cement No. 3 7 Days
A	1	1445 1437 1442x 1441	2172 2230 2217x 2206	1492 1537 1510x 1513	2335 2245 2202x 2260	1897 1885 1832x 1871	2742 2670 2710x 2707
	2	1572 1582 1562x 1572	2302 2257 2266x 2275	1570 1535 1532 1545	2332 2342 2302x 2325	1967 1935 1960 1954	2827 2862 2850x 2846
B	1	1520 1478 1483x 1494	2413 2288 2363x 2355	1420 1448 1392x 1420	2256 2438 2413x 2369	1710 1788 1758x 1752	2708 2663 2640x 2670
	2	1525 1508 1501x 1511	2381 2400 2352x 2378	1412 1430 1426x 1423	2339 2352 2371x 2354	1737 1752 1763x 1751	2710 2648 2656x 2672
C	1	1650 1680 1745 1692	2860 2856 2856x 2857	1630 1650 1645 1642	2715 2690 2700x 2702	2175 2210 2235x 2207	3300 3360 3320x 3327
	2	1905 1880 1935x 1907	3085 2950 2900x 2978	1720 1820 1765x 1768	2925 2825 2875x 2875	2415 2310 2395x 2373	3450 3540 3585x 3525
D	1	1730 1710 1655 1698	2875 2825 2750x 2817	1815 1860 1825x 1833	2725 2850 2750x 2775	2150 2220 2240x 2203	3400 3375 3400x 3392
	2	1765 1840 1870x 1825	3025 3000 2875x 2967	1645 1815 1830x 1763	2925 2925 3050x 2967	2100 2132 2120 2117	3350 3450 3400x 3400
E	1	1638 1668 1618 1641	2670 2695 2715 2693	1525 1558 1613 1565	2363 2428 2358 2383	2108 2040 2100 2083	3178 3070 3203 3150
	2	1438 1528 1515x 1494	2485 2448 2533x 2489	1370 1333 1383x 1362	2140 2285 2260x 2228	2008 2005 2023 2012	2950 3088 3135 3058

Co-Operative Tests of Portland Cement
Series of 1956

Table VIII

Part 2

COMPRESSIVE STRENGTH of Hydraulic Cement Mortars
A.S.T.M. Designation: C109-54T

Laboratory Code	Test Number	Cement No. 1		Cement No. 2		Cement No. 3	
		3 Days	7 Days	3 Days	7 Days	3 Days	7 Days
F	1	1700 1700 1800x 1733	2700 2700 2650 2683	1650 1600 1600 1617	2650 2600 2500 2583	2070 2170 2020 2087	3200 3200 3150 3183
	2	1800 1830 1850x 1827	2600 2650 2650 2633	1750 1660 1650 1687	2700 2600 2550 2617	2185 2125 2100 2137	3100 3100 3150 3117
G	1	1825 1825 1850x 1833	2650 2500 2500 2550	1650 1575 1500 1575	2200 2350 2150x 2233	2100 2025 2250 2125	2950 3100 3175 3075
	2	1785 1795 1780x 1787	2550 2580 2585 2572	1540 1520 1470x 1510	1975 2150 2300x 2142	2310 2235 2025 2190	3150 3100 3250 3167
H	1	1700 1700 1700 1700	2500 2600 2700 2600	1650 1500 1600 1583	2200 2200 2400x 2266	2200 2200 2300x 2233	3100 3050 3250 3133
	2	1700 1700 1700 1700	2600 2600 2550 2583	1500 1550 1500x 1516	2050 2100 2000x 2050	1900 2150 2000 2017	2800 2950 2800x 2850
I	1	1525 1525 1600x 1550	2425 2450 2425x 2433	1550 1550 1575 1558	2575 2625 2475 2558	1775 2200 1825x 1933	3100 2875 2975 2983
	2	1400 1375 1500x 1425	2550 2475 2250x 2425	1625 1500 1550 1558	2650 2650 2600x 2633	1900 2050 2000 1983	3025 2950 3025 3000
J	1	1582 1670 1600 1617	2375 2392 2402x 2390	1555 1490 1492x 1512	2180 2220 2310x 2237	2055 2062 2012 2043	3025 3125 3000 3050
	2	1610 1692 1622 1641	2575 2600 2625 2600	1525 1555 1572 1551	2232 2307 2265x 2268	2015 2125 2052 2064	3000 2975 2950 2975

Co-Operative Tests of Portland Cement
Series of 1956

Table VIII

Part 3

COMPRESSIVE STRENGTH of Hydraulic Cement Mortars
A.S.T.M. Designation: C109-54T

Laboratory Code	Test Number	Cement No. 1		Cement No. 2		Cement No. 3	
		3 Days	7 Days	3 Days	7 Days	3 Days	7 Days
K	1	1625	2525	1700	2575	2050	2950
		1600	2575	1700	2550	2025	3050
		1575x	2500	1575	2475	2025	3125
		1600	2533	1658	2533	2033	3042
	2	1675	2400	1575	2475	1975	2800
		1675	2475	1600	2400	1925	2875
		1700	2550x	1625	2525x	1875x	2700x
		1683	2475	1600	2467	1925	2792
L	1	1650	2627	1690	2927	2212	3090
		1752	2577	1747	2912	2147	3240
		1692	2592	1777x	2887x	2052	3270
		1698	2599	1738	2909	2137	3200
	2	1582	2712	1510	2787	2087	3175
		1507	2585	1777	2625	2110	3162
		1557x	2575	1765x	2745x	2135	3287
		1548	2624	1684	2719	2110	3208
M	1	1813	2823	1795	2725	2315	3413
		1785	3017	1900	2565	2295	3298
		1865x	2978x	1708x	2683x	2120x	3525x
		1821	2939	1801	2658	2243	3412
	2	1825	3085	1812	2668	2315	2653
		1913	2922	1795	2765	2443	2910
		1913x	3090x	1828x	2840x	2250x	3258x
		1884	3032	1812	2758	2336	2940
Average		1666	2603	1608	2495	2074	3072
Per Cent of Tests in Control **		34.6	42.3	46.2	19.2	57.7	53.8
Repeatability-Absolute		106.0	151.5	142.2	201.4	207.8	228.5
Repeatability %		6.3	5.8	8.9	8.0	10.0	7.4
Reproducibility-Absolute		106.0	156.9	144.6	310.9	198.2	245.5
Reproducibility %		6.3	6.0	9.1	12.3	9.6	7.9

** Based on tests in Control
x Indicates tests out of Control

Co-Operative Tests of Portland Cement
Series of 1956

Table IX

WATER REQUIRED for Flow of 108 Per Cent in C109 Mortar, Determined by Two or More Tests and Interpolation of Data, of Three Portland Cements Designated by 1, 2, and 3, and Thirteen Laboratories Designated A to M

Laboratory Code	Cement No. 1	Cement No. 2	Cement No. 3
A	245	234	240
B	239	229	234
C	260	248	246
D	246	228	238
E	250	245	250
F	235	229	236
G	246	235	242
H	243	228	239
I	254	-	247
J	252	238	246
K	-	240	246
L	252	237	225
M	273	254	261
Average	250	237	242
Minimum	235	228	225
Maximum	273	254	261

Co-operative Tests of Portland Cement
Series of 1956

Table X

AUTOCLAVE EXPANSION
of Three Portland Cements
Designated 1, 2 and 3, by Twelve Laboratories
Designated A to M, According to
A.S.T.M. Designation: C151-54

Laboratory Code	Test Number	Cement Number 1	Cement Number 2	Cement Number 3
A	1	.025	-.005	.197
	2	.033	.000	.221
B	1	.031	.004	.235
	2	.024	.000	.246
C	1	.033x	-.002	.234
	2	.036x	-.005	.220
D	1	.016x	-.020x	.221
	2	.020x	-.023x	.219
E	1	.026	-.006	.212
	2	.035	.006	.250
F	1	.030	.010x	.210
	2	.030	.001x	.210
G	1	.027	.012x	.198x
	2	.029	.008x	.190x
H	1	.020x	-.017x	.233
	2	.020x	-.029x	.200
I	1	.028	.002x	.214
	2	.024	.009x	.232
J	1	.020x	-.010	.220
	2	.020x	-.010	.230
L	1	.027	-.008	.222
	2	.026	-.008	.222
M	1	.026	-.013x	.240
	2	.022	-.020x	.234
Average		.026	.005	.221
% Tests in Control		66.7	50.0	91.7
Repeatability:				
Absolute		.012	.015	.042
Percent		44.6	395.4	18.7
Reproducibility:				
Absolute**		.007	.017	.031
Percent		26.2	452.4	14.1

**Based on tests in control
x Indicates tests out of control

Co-Operative Tests of Portland Cement
Series of 1956

Table XI

AIR CONTENT of Three Portland Cements Designated 1, 2 and 3, by Thirteen Laboratories Designated A to L According to A.S.T.M. Designation: C185-53T

Laboratory Code	Test Number	Cement No. 1	Cement No. 2	Cement No. 3
A	1 2	7.6 7.7	5.1 5.2	6.9 6.8
B	1 2	9.6 9.3	6.0 6.3	4.7 4.6
C	1 2	7.8 7.9	5.4 5.2	6.8 6.3
D	1 2	10.8 -	5.3 -	5.6 -
E	1 2	8.7 -	5.4 -	7.8 -
F	1 2	9.5 9.3	7.0 7.2	8.6 8.3
G	1 2	6.6 6.9	3.9 3.7	6.8 6.4
H	1 2	7.6 6.7	3.9 4.3	7.0 7.6
I	1 2	10.0 10.0	7.0 7.8	8.2 8.5
J	1 2	8.9 9.1	6.3 5.9	7.9 8.4
K	1 2	8.3 8.7	- -	7.5 8.2
L	1 2	7.3 7.4	5.4 4.8	6.6 6.2
M	1 2	6.3 6.4	4.2 4.4	4.9 5.5
Average Minimum Maximum		8.3 6.3 10.8	5.4 3.7 7.8	6.9 4.6 8.6

Co-Operative Tests of Portland Cement
Series of 1956

Table XII

WATER REQUIRED for Flow of 88 Per Cent
in C185 Mortar Determined by Two or More Tests
and Interpolation of Data. Three Cements
Designated 1, 2, and 3, and Thirteen Laboratories
Designated A to M

Laboratory Code	Cement No. 1	Cement No. 2	Cement No. 3
A	200	199	208
B	204	208	210
C	210	212	214
D	201	194	204
E	217	224	217
F	210	212	213
G	208	215	216
H	200	215	200
I	216	-	218
J	223	237	223
K	207	-	208
L	212	212	221
M	222	224	225
Average	210	214	214
Minimum	200	194	200
Maximum	223	224	225

Co-Operative Tests of Portland Cement
Series of 1956

Table XIII - Part 1

FALSE SET of Portland Cement. Three Cements Designated 4, 5, and 6, and Thirteen Laboratories Designated A to M, According to A.S.T.M. Designation: 359-55T

Laboratory Code	Test Number	Penetration in Millimeters				
		Cement No. 4				
		Initial	5 Min.	8 Min.	11 Min.	Remix
A	1 2	50 50	50 50	50 50	50 50	50 50
B	1 2	50+ 50+	50+ 50+	50+ 50+	50+ 50+	50+ 50+
C	1 2	50+ 50+	50+ 50+	50+ 50+	50+ 50+	50+ 50+
D	1 2	50+ 50+	50+ 50+	50+ 50+	50+ 50+	50+ 50+
E	1 2	50+ 50+	50+ 50+	50 49	47 48	50+ 50+
F	1 2	50 50	50 50	50 50	50 50	50 50
G	1 2	50 50	50 50	50 50	50 50	50 50
H	1 2	50 50	50 50	50 50	50 50	50 50
I	1 2	50 50	50 50	50 50	50 50	50 50
J	1 2	50+ 50+	50+ 50+	50+ 50+	50+ 50+	50+ 50+
K	1 2	50+ 50+	50+ 50+	50+ 50+	50+ 50+	50+ 50+
L	1 2	50+ 50+	50+ 50+	50+ 50+	50+ 50+	50+ 50+
M	1 2	50+ 50+	50+ 50+	50+ 50+	50+ 50+	50+ 50+
Average Minimum Maximum		50+ 50 50+	50+ 50 50+	50+ 49 50+	50+ 47 50+	50+ 50 50+

Co-Operative Tests of Portland Cement
Series of 1956

Table XIII - Part 2

FALSE SET of Portland Cement. Three Cements Designated 4, 5, and 6, and Thirteen Laboratories Designated A to M, According to A.S.T.M. Designation 359-55T

Laboratory Code	Test Number	Penetration in Millimeters				
		Cement No. 5				
		Initial	5 Min.	8 Min.	11 Min.	Remix
A	1	50	4	2	2	50
	2	50	4	2	2	50
B	1	50+	42	14	6	50+
	2	50+	47	10	7	50+
C	1	50+	32	11	8	50+
	2	50+	48	7	5	50+
D	1	50+	34	9	6	50+
	2	50+	45	7	5	50+
E	1	50+	14	3	1	50+
	2	50+	4	1	1	50+
F	1	50	32	4	3	50
	2	50	29	4	3	50
G	1	50	46	10	6	50
	2	50	48	10	8	50
H	1	50	43	6	4	50
	2	50	42	7	3	50
I	1	50	30	7	5	50
	2	50	45	6	6	50
J	1	50+	50+	6	4	50+
	2	50+	50+	6	5	50+
K	1	50+	45	12	10	50+
	2	50+	44	9	8	50+
L	1	50+	46	12	6	50+
	2	50+	46	9	5	50+
M	1	50+	47	14	9	50+
	2	50+	48	11	9	50+
Average		50+	37	8	5	50+
Minimum		50	4	1	1	50
Maximum		50+	50+	14	10	50+

Co-Operative Tests of Portland Cement
Series of 1956

Table XIII - Part 3

FALSE SET of Portland Cement. Three Cements Designated 4, 5, and 6, and Thirteen Laboratories Designated A to M, According to A.S.T.M. Designation: 359-55T

Laboratory Code	Test Number	Penetration in Millimeters				
		Cement No. 6				
		Initial	5 Min.	8 Min.	11 Min.	Remix
A	1	50	12	1	0	50
	2	50	5	2	0	50
B	1	50+	50+	32	12	50+
	2	50+	50+	42	8	50+
C	1	50+	19	8	5	50+
	2	50+	50	16	6	50+
D	1	50+	50	7	3	50+
	2	50+	50	10	5	50+
E	1	50+	8	3	1	50+
	2	50+	3	1	1	50+
F	1	50	39	5	3	50
	2	50	34	5	3	50
G	1	50	50	8	7	50
	2	50	50	9	6	50
H	1	50	50	8	5	50
	2	50	47	8	4	50
I	1	50	49	4	4	50
	2	50	48	4	3	50
J	1	50+	50+	7	4	50+
	2	50+	50+	9	7	50+
K	1	50+	50+	23	7	50+
	2	50+	50	7	5	50+
L	1	50+	50+	35	5	50+
	2	50+	50+	22	5	50+
M	1	50+	50+	35	12	50+
	2	50+	50+	11	8	50+
Average		50+	41	12	5	50+
Minimum		50	3	1	0	50
Maximum		50+	50+	42	12	50+

Co-operative Tests of Portland Cement
Series of 1956

Table XIV

FALSE SET
of Portland Cement
Three Cements Designated 4, 5 and 6, and Thirteen
Laboratories Designated A to M, According to
Federal Specifications SS-C-158c, 4.4.11

Laboratory Code	Test Number	Penetration in Millimeters					
		Cement No. 4		Cement No. 5		Cement No. 6	
		Initial	5 Min.	Initial	5 Min.	Initial	5 Min.
A	1	33	21	34	8	35	4
	2	34	23	33	8	34	3
B	1	37	24	26	12	40+	14
	2	34	23	30	9	37	5
C	1	37	27	34	8	33	10
	2	33	32	33	7	37	3
D	1	37	31	33	7	36	7
	2	36	28	36	8	37	5
E	1	35	25	34	8	35	4
	2	33	26	37	7	37	4
F	1	35	28	36	15	36	11
	2	33	29	33	13	33	14
G	1	36	26	33	11	37	19
	2	35	22	30	11	36	17
H	1	37	25	34	5	37	5
	2	34	24	35	5	36	5
I	1	37	23	33	6	37	8
	2	33	21	34	6	37	7
J	1	37	27	37	12	36	5
	2	36	28	34	8	37	5
K	1	36	26	35	15	36	7
	2	35	24	33	16	34	9
L	1	34	21	33	15	36	7
	2	33	22	35	20	35	8
M	1	37	27	36	12	37	7
	2	36	26	35	13	35	4
Average		35	25	34	10	36	8
Minimum		33	21	26	5	33	3
Maximum		37	32	37	20	40+	19

Co-operative Tests of Portland Cement
Series of 1956

Table XV

FALSE SET
of Portland Cement
Three Cements Designated 4, 5 and 6, and Twelve
Laboratories Designated A to M According to
Test Method No. Calif. 503A

Laboratory Code	Test Number	Flow and Penetration in Millimeters					
		Cement #4		Cement #5		Cement #6	
		Flow	5 Min. Pen.	Flow	5 Min. Pen.	Flow	5 Min. Pen.
A	1	101	50	102	7	103	5
	2	104	50	106	23	105	23
B	1	107	28	102	12	101	13
	2	109	26	105	10	106	15
C	1	108	36	108	22	101	16
	2	107	36	108	19	110	13
E	1	106	34	106	11	106	15
	2	100	33	108	15	102	12
F	1	104	12	110	7	102	5
	2	104	10	110	5	101	4
G	1	108	34	103	16	109	19
	2	108	36	102	14	109	20
H	1	106	32	103	8	102	12
	2	108	34	104	10	103	14
I	1	104	35	104	21	104	12
	2	108	31	106	16	108	12
J	1	103	24	106	11	104	8
	2	106	33	106	10	104	13
K	1	109	36	104	11	105	14
	2	103	33	104	8	101	11
L	1	107	32	101	18	104	26
	2	109	34	102	18	102	26
M	1	103	38+	105	28	106	28
	2	106	38+	105	25	106	35+
Average		106	33	105	15	104	15
Minimum		100	10	101	5	101	5
Maximum		109	50	110	28	110	35+

Co-Operative Tests of Portland Cement
Series of 1956

Table XVI

SPECIFIC GRAVITY of Portland Cement
Three Cements Designated 1, 2, and 3, and
Thirteen Laboratories Designated A to M
According to A.S.T.M. Designation: C188-44

Laboratory Code	Test Number	Cement No. 1	Cement No. 2	Cement No. 3
A	1	3.216	3.168	3.184
	2	3.157	3.148	3.134
B	1	3.12	3.14	3.03
	2	3.14	3.14	3.03
C	1	3.14	3.17	3.09
	2	3.14	3.18	3.11
D	1	3.16	3.19	3.10
	2	3.14	-	3.11
E	1	3.15	3.16	3.12
	2	3.17	3.18	3.09
F	1	3.16	3.20	3.12
	2	3.17	3.20	3.12
G	1	3.14	3.182	3.09
	2	3.17	3.16	3.08
H	1	3.15	3.13	3.06
	2	3.15	3.13	3.08
I	1	3.10	3.06	3.13
	2	3.12	3.06	3.15
J	1	3.15	3.19	3.11
	2	3.15	3.18	3.11
K	1	3.13	3.17	3.11
	2	3.14	3.18	3.10
L	1	3.192	3.176	3.115
	2	3.186	3.176	3.115
M	1	3.153	3.188	3.129
	2	3.160	3.168	3.130
Average		3.15	3.16	3.11
Minimum		3.10	3.06	3.03
Maximum		3.216	3.20	3.18

Co-Operative Tests of Portland Cement
Series of 1956
Table XVII
CHEMICAL ANALYSIS of Portland Cement for SILICON DIOXIDE
Three Cements Designated 1, 2, and 3, and
Thirteen Laboratories Designated A to M
According to A.S.T.M. Designation: C114-53

Laboratory Code	Test Number	Cement No. 1	Cement No. 2	Cement No. 3
A	1	22.72	24.50	20.54
	2	22.72	24.54	20.58
B	1	22.98	24.80	20.66
	2	22.96	24.76	20.58
C	1	22.96	24.76	20.62
	2	22.84	24.65	20.64
D	1	22.86	24.82	20.60
	2	22.76	24.74	20.52
E	1	23.18	25.15	20.98
	2	23.12	24.96	20.90
F	1	22.86	24.76	20.64
	2	22.90	24.68	20.60
G	1	22.90	24.52	20.40
	2	22.94	24.54	20.42
H	1	22.64	24.50	20.28
	2	22.70	24.42	20.38
I	1	23.16	25.08	20.88
	2	23.56	25.26	20.76
J	1	22.90	24.72	20.60
	2	22.78	24.66	20.66
K	1	23.04	24.76	20.50
	2	22.92	24.78	20.60
L	1	23.00	24.96	20.84
	2	23.08	25.10	20.94
M	1	22.25	24.42	19.68
	2	22.18	24.25	19.74
Average		22.88	24.73	20.56
Minimum		22.18	24.25	19.68
Maximum		23.56	25.26	20.98

Co-Operative Tests of Portland Cement
Series of 1956

Table XVIII

CHEMICAL ANALYSIS of Portland Cement for ALUMINUM OXIDE
Three Cements Designated 1, 2, and 3, and
Thirteen Laboratories Designated A to M
According to A.S.T.M. Designation: C114-53

Laboratory Code	Test Number	Cement No. 1	Cement No. 2	Cement No. 3
A	1	4.38	2.83	5.73
	2	4.38	2.83	5.53
B	1	4.28	2.81	5.38
	2	4.33	2.87	5.34
C	1	4.36	2.89	5.28
	2	4.54	2.96	5.39
D	1	4.31	2.82	5.43
	2	4.40	2.72	5.41
E	1	4.42	3.06	5.42
	2	4.02	2.44	5.34
F	1	4.28	2.72	4.97
	2	4.31	2.66	5.08
G	1	4.13	2.71	5.24
	2	4.21	2.69	5.30
H	1	4.20	2.67	5.30
	2	4.26	2.71	5.14
I	1	4.12	2.88	5.12
	2	4.00	2.64	4.92
J	1	4.27	2.73	5.30
	2	4.29	2.79	5.26
K	1	4.24	2.87	5.48
	2	4.34	2.73	5.30
L	1	4.41	2.94	5.68
	2	4.51	2.92	5.56
M	1	4.61	3.06	5.84
	2	4.62	3.23	5.87
Average		4.32	2.81	5.37
Minimum		4.00	2.44	4.92
Maximum		4.62	3.23	5.87

Co-Operative Tests of Portland Cement
Series of 1956

Table XIX

CHEMICAL ANALYSIS of Portland Cement for FERRIC OXIDE
Three Cements Designated 1, 2, and 3, and
Thirteen Laboratories Designated A to M
According to A.S.T.M. Designation: C114-53

Laboratory Code	Test Number	Cement No. 1	Cement No. 2	Cement No. 3
A	1	2.90	2.67	3.25
	2	2.90	2.67	3.25
B	1	2.98	2.71	3.36
	2	2.95	2.71	3.36
C	1	2.90	2.65	3.28
	2	2.86	2.60	3.25
D	1	2.97	2.72	3.25
	2	2.92	2.70	3.25
E	1	2.82	2.60	3.20
	2	2.82	2.56	3.20
F	1	2.96	2.68	3.43
	2	2.95	2.70	3.48
G	1	2.85	2.61	3.22
	2	2.85	2.61	3.22
H	1	2.82	2.59	3.28
	2	2.82	2.59	3.28
I	1	2.96	2.56	3.28
	2	2.88	2.72	3.26
J	1	2.87	2.63	3.22
	2	2.85	2.61	3.24
K	1	2.88	2.67	3.28
	2	2.90	2.67	3.30
L	1	2.81	2.54	3.16
	2	2.81	2.54	3.16
M	1	2.91	2.67	3.31
	2	2.92	2.67	3.31
Average		2.89	2.64	3.27
Minimum		2.81	2.54	3.16
Maximum		2.98	2.72	3.48

Co-operative Tests of Portland Cement
Series of 1956

Table XX

CHEMICAL ANALYSIS
of Portland Cement for
CALCIUM OXIDE
Three Cements Designated 1, 2 and 3, and
Thirteen Laboratories Designated A to M
According to A.S.T.M. Designation: C114-53

Laboratory Code	Test Number	Cement Number		
		1	2	3
A	1	65.24	65.96	62.04
	2	64.87	65.82	61.84
B	1	64.85	65.67	61.79
	2	64.79	65.69	61.56
C	1	64.90	65.80	62.00
	2	65.00	65.70	62.00
D	1	64.78	65.98	61.60
	2	64.88	65.92	61.75
E	1	64.97	65.92	62.09
	2	65.16	65.92	62.18
F	1	65.30	65.90	62.20
	2	65.20	65.80	62.00
G	1	65.21	66.13	62.04
	2	65.09	66.03	61.93
H	1	64.85	65.66	61.88
	2	64.75	65.63	61.88
I	1	64.94	65.94	61.82
	2	65.14	66.50	62.08
J	1	64.68	65.66	61.58
	2	64.60	65.68	61.48
K	1	64.92	65.71	61.70
	2	64.72	65.72	61.70
L	1	64.98	65.78	61.88
	2	64.98	65.88	61.88
M	1	64.43	64.90	61.40
	2	64.60	64.54	61.24
Average		64.92	65.76	61.83
Minimum		64.43	64.54	61.24
Maximum		65.30	66.50	62.20

Co-Operative Tests of Portland Cement
Series of 1956

Table XXI

CHEMICAL ANALYSIS of Portland Cement for MAGNESIUM OXIDE
Three Cements Designated 1, 2, and 3, and
Thirteen Laboratories Designated A to M
According to A.S.T.M. Designation: C114-53

Laboratory Code	Test Number	Cement No.		
		1	2	3
A	1	1.02	1.19	4.46
	2	1.08	1.19	4.43
B	1	1.77	1.05	4.39
	2	1.77	1.09	4.55
C	1	1.52	0.87	4.11
	2	1.52	0.90	4.10
D	1	1.16	0.65	3.20
	2	1.20	0.70	3.30
E	1	1.45	0.86	3.95
	2	1.53	1.11	3.89
F	1	1.75	1.00	4.18
	2	1.79	1.00	4.20
G	1	1.49	0.87	4.12
	2	1.51	0.89	4.08
H	1	1.50	0.83	4.24
	2	1.58	0.83	4.17
I	1	1.67	0.96	4.13
	2	1.74	0.86	4.45
J	1	1.71	0.90	4.25
	2	1.67	0.93	4.30
K	1	1.63	0.99	4.34
	2	1.66	1.02	4.16
L	1	1.51	0.86	4.24
	2	1.57	0.90	4.26
M	1	1.79	1.49	4.64
	2	1.74	1.77	4.70
Average		1.55	0.99	4.19
Minimum		1.02	0.65	3.20
Maximum		1.79	1.77	4.70

Co-Operative Tests of Portland Cement
Series of 1956

Table XXII

CHEMICAL ANALYSIS of Portland Cement for IGNITION LOSS
Three Cements Designated 1, 2, and 3, and
Thirteen Laboratories Designated A to M
According to A.S.T.M. Designation: C114-53

Laboratory Code	Test Number	Cement No. 1	2	3
A	1	1.46	0.73	1.68
	2	1.07	0.75	1.70
B	1	0.89	0.59	1.73
	2	0.95	0.54	1.65
C	1	1.00	0.67	1.80
	2	0.99	0.65	1.80
D	1	1.31	1.18	2.09
	2	1.20	1.06	2.09
E	1	0.96	0.68	1.75
	2	0.95	0.66	1.76
F	1	0.84	0.86	1.81
	2	0.80	0.85	1.89
G	1	1.05	0.94	1.98
	2	1.10	0.96	2.03
H	1	1.06	0.63	1.78
	2	0.97	0.67	1.82
I	1	1.06	0.70	1.83
	2	1.01	0.72	1.81
J	1	1.15	0.80	1.87
	2	1.11	0.82	1.88
K	1	0.99	0.70	1.79
	2	1.06	0.76	1.84
L	1	0.98	0.65	1.80
	2	1.00	0.71	1.80
M	1	1.13	0.95	2.03
	2	1.09	0.97	2.05
Average		1.05	0.78	1.85
Minimum		0.80	0.54	1.65
Maximum		1.46	1.18	2.09

Co-Operative Tests of Portland Cement
Series of 1956

Table XXIII

CHEMICAL ANALYSIS of Portland Cement for INSOLUBLE RESIDUE
Three Cements Designated 1, 2, and 3, and
Thirteen Laboratories Designated A to M
According to A.S.T.M. Designation: C114-53

Laboratory Code	Test Number	Cement No.		
		1	2	3
A	1	0.27	0.08	0.16
	2	0.27	0.08	0.15
B	1	0.23	0.08	0.13
	2	0.24	0.05	0.12
C	1	0.30	0.05	0.12
	2	0.24	0.05	0.10
D	1	0.18	0.04	0.09
	2	0.15	0.05	0.08
E	1	0.24	0.05	0.10
	2	0.20	0.04	0.07
F	1	0.26	0.05	0.08
	2	0.26	0.05	0.05
G	1	0.18	0.05	0.10
	2	0.17	0.06	0.08
H	1	0.14	0.02	0.03
	2	0.16	0.04	0.05
I	1	0.28	0.03	0.07
	2	0.20	0.05	0.04
J	1	0.24	0.04	0.09
	2	0.22	0.08	0.06
K	1	-	-	-
	2	0.23	0.05	0.01
L	1	0.23	0.12	0.03
	2	0.27	0.15	0.07
M	1	0.21	0.05	0.21
	2	0.27	0.07	0.15
Average		0.23	0.06	0.09
Minimum		0.14	0.02	0.01
Maximum		0.30	0.15	0.21

Co-Operative Tests of Portland Cement
Series of 1956

Table XXIV

CHEMICAL ANALYSIS of Portland Cement for SULFUR TRIOXIDE
Three Cements Designated 1, 2, and 3, and
Thirteen Laboratories Designated A to M
According to A.S.T.M. Designation: C114-53

Laboratory Code	Test Number	Cement No.		
		1	2	3
A	1	1.78	1.98	1.98
	2	1.75	2.03	1.99
B	1	1.88	2.13	2.04
	2	1.89	2.12	2.06
C	1	1.91	2.11	2.07
	2	1.89	2.08	2.04
D	1	1.91	2.12	2.09
	2	1.88	2.08	2.03
E	1	1.93	2.12	1.98
	2	1.89	2.04	1.92
F	1	1.87	1.97	1.84
	2	1.88	1.98	1.88
G	1	1.78	2.00	2.00
	2	1.79	2.04	2.05
H	1	1.88	2.02	2.00
	2	1.84	2.00	1.98
I	1	1.91	1.97	2.00
	2	1.85	2.04	1.96
J	1	1.93	2.13	2.07
	2	1.93	2.12	2.11
K	1	1.93	2.11	2.09
	2	1.93	2.12	2.10
L	1	1.88	2.07	2.03
	2.	1.91	2.11	2.07
M	1	1.91	2.12	2.03
	2	1.91	2.14	2.04
Average		1.88	2.07	2.02
Minimum		1.75	1.97	1.84
Maximum		1.93	2.14	2.11

Co-operative Tests of Portland Cement
Series of 1956

Table XXV

CHEMICAL ANALYSIS
of Portland Cement for
CALCIUM SULFATE
in Hydrated Portland Cement Mortar
Three Cements Designated 1, 2 and 3, and
Twelve Laboratories Designated A to M
According to A.S.T.M. Designation: C265-54T

Laboratory Code	Test Number	Cement Number		
		1	2	3
A	1	0.02	0.46	0.01
	2	0.02	0.41	0.01
B	1	0.01	0.52	0.13
	2	0.01	0.49	0.12
C	1	0.02	0.51	Trace
	2	0.02	0.53	Trace
D	1	0.02	0.50	0.01
	2	----	----	----
F	1	0.04	0.43	0.01
	2	0.04	0.50	0.01
G	1	0.01	0.46	0.01
	2	0.01	0.43	0.02
H	1	0.00	0.45	0.00
	2	0.00	0.41	0.00
I	1	0.09	0.56	0.02
	2	0.08	0.52	0.06
J	1	----	0.48	0.01
	2	0.02	0.48	0.01
K	1	0.01	0.50	0.00
	2	0.06	0.69	0.03
L	1	0.01	0.99	0.00
	2	0.02	0.90	0.01
M	1	0.00	0.44	0.00
	2	0.00	0.45	0.01
Average		0.02	0.53	0.02
Minimum		0.00	0.41	0.00
Maximum		0.09	0.99	0.13

Co-Operative Tests of Portland Cement
Series of 1956

Table XXVI

CHEMICAL ANALYSIS of Portland Cement for SODIUM OXIDE
Three Cements Designated 1, 2, and 3, and
Eleven Laboratories Designated A to M
According to A.S.T.M. Designation: C 228-49T

Laboratory Code	Test Number	Cement No. 1	Cement No. 2	Cement No. 3
A	1 2	0.42 0.41	0.10 0.11	0.56 0.56
B	1 2	0.40 0.40	0.12 x 0.12	0.57 0.57
C	1 2	0.42 0.40	0.09 x 0.08	0.54 x 0.54
E	1 2	0.42 0.42	0.13 x 0.13	0.58 x 0.58
G	1 2	0.41 0.42	0.10 0.12	0.54 x 0.54
H	1 2	0.43 x 0.44	0.10 0.10	0.57 0.58
I	1 2	0.43 0.42	0.10 0.11	0.58 0.57
J	1 2	0.46 x 0.46	0.11 0.11	0.62 x 0.62
K	1 2	0.43 0.41	0.10 0.09	0.60 x 0.58
L	1 2	0.35 x 0.36	0.05 x 0.08	0.51 x 0.54
M	1 2	0.39 x 0.40	0.10 0.10	0.53 x 0.52
Average		0.41	0.10	0.56
Per Cent of Tests in Control		36.4	36.4	63.6
** Repeatability-Absolute		0.027	0.021	0.016
** " - %		6.5	20.7	2.9
** Reproducibility-Absolute		0.028	0.019	0.029
** " - %		6.8	18.5	5.1

** Based on tests in Control
x Indicates tests out of Control

Co-Operative Tests of Portland Cement
Series of 1956

Table XXVII

CHEMICAL ANALYSIS of Portland Cement of POTASSIUM OXIDE
Three Cements Designated 1, 2, and 3, and
Eleven Laboratories Designated A to M
According to A.S.T.M. Designation: C 228-49T

Laboratory Code	Test Number	Cement No. 1	Cement No. 2	Cement No. 3
A	1 2	0.20 0.20	0.13 x 0.13	0.45 x 0.46
B	1 2	0.18 x 0.18	0.10 x 0.10	0.45 x 0.45
C	1 2	0.20 0.19	0.12 0.12	0.45 x 0.45
E	1 2	0.18 x 0.19	0.11 0.12	0.48 0.47
G	1 2	0.22 0.20	0.14 x 0.12	0.51 x 0.48
H	1 2	0.21 0.21	0.12 0.12	0.49 0.49
I	1 2	0.22 0.20	0.13 0.12	0.51 x 0.51
J	1 2	0.21 0.21	0.12 0.12	0.49 0.50
K	1 2	0.21 0.21	0.13 0.12	0.51 x 0.50
L	1 2	0.19 0.21	0.11 0.12	0.48 x 0.51
M	1 2	0.18 x 0.18	0.11 0.11	0.44 x 0.44
Average		0.20	0.12	0.48
Per Cent of Tests in Control		72.7	72.7	27.3
** Repeatability-Absolute		0.027	0.015	0.020
" %		13.1	12.6	4.1
** Reproducibility-Absolute		0.021	0.017	0.024
" %		10.1	14.6	4.9

** Based on tests in Control
x Indicates tests out of Control